

APPLYING SYSTEMS MODELING AND CASE STUDY METHODOLOGIES TO
DEVELOP BUILDING INFORMATION MODELING FOR MASONRY
CONSTRUCTION

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Bryan Lee

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APPLYING SYSTEMS MODELING AND CASE STUDY METHODOLOGIES TO
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CONSTRUCTION

Approved by:

Dr. Russell Gentry, Advisor
Schools of Architecture and Civil and
Environmental Engineering
Georgia Institute of Technology

Dr. Charles Eastman
School of Architecture and College of
Computing
Georgia Institute of Technology

Dr. Yong K. Cho
School of Civil and Environmental
Engineering
Georgia Institute of Technology

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GLOSSARY

3D	Three-dimensional
act	Activity diagram (Note: Written without abbreviation in text)
AEC	Architecture, Engineering, and Construction
bdd	Block definition diagram
BIM	Building Information Modeling
BIM-M	Building Information Modeling for Masonry (Initiative)
BPMN	Business Process Modeling Notation
CMU	Concrete Masonry Unit
EBB	Engineered Biosystems Building
ibd	Internal block diagram
IPD	Interdisciplinary Project Delivery
IT	Information Technology
LOD	Level of Development
par	Parametric diagram
pkg	Package diagram
req	Requirement diagram
RFI	Request for Information
seq	Sequence diagram
stm	State machine diagram
SysML	Systems Modeling Language
uc	Use case diagram

SUMMARY

Building Information Modeling, or BIM, is a digital representation of physical and functional characteristics of a facility that serves as a shared resource for information for decision-making throughout the project lifecycle (National Institute of Building Sciences, 2007). The masonry construction industry currently suffers from the lack of BIM integration. Where other industries and trades have increased productivity by implementing standards for software-enhanced workflows, masonry construction has failed to adopt information tools and processes. New information technology and process modeling tools have grown in popularity and their use is helping to understand and improve construction processes. The Systems Modeling Language, or SysML, is one of the process modeling tools we can use to model and analyze the various processes and workflows. In this research, a case study methodology was applied to analyze the masonry construction industry to understand the current state of masonry construction processes and workflows. This thesis reviews these concepts and the applied case studies which are necessary to move forward with the implementation of BIM for masonry.

CHAPTER 1

MASONRY CONSTRUCTION

1.1 Background on Masonry Construction

1.1.1 History

Some of the oldest and most revered buildings in the history of our planet were constructed using masonry, including the Egyptian Pyramids, the Coliseum, the Taj Mahal, and the Great Wall of China. Over 6000 years later, masonry is still used today (Masonry Contractors Association of America, 2015). As part of contemporary masonry construction, improved products and processes have been developed but the nature of masonry construction remains: small groups of masons and labors place mortar and units together to form masonry building elements. As other construction systems are developed to facilitate faster construction and off-site pre-fabrication, masonry construction must adopt the developing technologies and practices in order to remain competitive. Due to the nature of masonry construction, it may not be as efficient or effective as the construction industry continues to advance.

1.1.2 Elements and Processes of Masonry Construction

1.1.2.1 Materials and Equipment

Masonry construction involves many different items, due to the wide range of activities and requirements associated with the trade. First, there are many types of masonry units, including tile and cast and cut stone. But brick and concrete masonry units (CMU) remain the primary products used (Masonry Contractors Association of America, 2015). In addition to the basic building units, masonry involves numerous, supplementary materials, including mortar, grout, coatings, ties, anchors, and reinforcement, that are applied in and to the masonry wall as it

is being constructed. Furthermore, during the process of masonry construction, a wide range of equipment are used, including scaffolds, shores, hoists, cranes, and forklifts (Hunter, 1997; R. C. Smith, Honkala, & Andres, 1979).

1.1.2.2 Basic Stakeholders and Activities

Much of masonry construction involves two key groups of stakeholders: the general contractor or construction manager (GC/CM) and the mason subcontractor. This thesis primarily concerns the interactions of these two groups and their employees, but also considers other stakeholders involved in the overall design and construction project timeline, such as the owner, architect, and engineer.

The mason subcontractor has various employees involved in the process of construction. The scope of work is usually organized into different wall sections with crews assigned to specific tasks (Ng & Tang, 2010). The mason crew is made up of masons, who lay bricks and blocks, and laborers, who help make the unit laying process more efficient and support the productivity of the mason, who is the highest skill and wage rate of the crew. Laborers can also be assigned to other supporting tasks such as moving mortar, erecting scaffolds, and handling reinforcement. The forklift operator moves masonry units around a site to the masons and laborers, the saw operator cuts the bricks and blocks, and the mixer operator mixes the mortar and grout that will be used by crews (Florez, Castro-Lacouture, & Gentry, 2014). The foreperson organizes and monitors the work of the masons and on a specific section, while doing quality control and coordinating with other forepersons in the same and other trades (Florez et al., 2014; Oregon Building Congress, 2015). The mason superintendent oversees the staffing of mason crews and its coordination with other crews and/or trades. The project manager plays a similar role to that of the superintendent but will also handles submittals, coordination with the design

team, and helps manage the flow of material and equipment to and from the job site (Oregon Building Congress, 2015). The supervisory roles, those allocated to the foreperson, the superintendent, and the project manager, may often be interchangeable, depending on the specific company or project scope. The GC/CM has similar positions, especially the supervising roles, but does not carry out the actual construction work done by its subcontractors, except in those situations where the general contractors self-perform that work. However, few general contractors self-perform masonry construction.

1.1.3 Implications of the Current Industry

Unlike other construction trades and industries which have benefited from standardization and advanced technology over the years (Baddoo, 2008; Kayali, 2008), masonry is still a traditional and manual form of construction. This suggests the possibility of having unique and specific issues during building construction. The recession and collapse of the housing market in the previous decade damaged the construction industry as a whole, and significantly reduced the demand for specifically masonry projects (Byun, 2010). Although the construction industry may be recovering, there are still a variety of issues, such as the lack of efficient organization and labor management, which may threaten the productivity and sustainability of masonry construction. Given the complexity of the construction industry, conducting research, let alone identifying issues for improvement, can be fairly difficult (Harty, 2005).

1.2 Problems in Masonry Construction

The issues in masonry construction can be technical, technological, and organizational in nature, and they can arise from physical, mental, and temporal pressures. A masonry project can be demanding on all of its stakeholders, including the GC/CM and subcontractors, and their

project managers, masons, and laborers (Mitropoulos & Memarian, 2013). The location and environment of a project, the timeline for completion, and the social dynamic on a jobsite will all affect the workload and performance of all stakeholders. Ultimately, the resulting errors and other problems can have significant, negative effects on the cost, time, safety, and quality on a project.

1.2.1 Pressures and Demands

1.2.1.1 Physical Labor

As with many tasks in construction and other similar industries, masonry construction involves very labor-intensive activities such as laying block, mixing mortar, and installing scaffolds. This work often requires masons and laborers to repeatedly lift heavy materials, stand for long periods of time (Florez et al., 2014), complete repetitive motions, and work in uncomfortable positions (Mitropoulos & Memarian, 2013).

In addition to the physical difficulties that arise from using various tools and equipment, the conditions of the worksite, the stakeholder relationships, and any other potential interruptions can increase stress and mistakes. Since masons usually work outdoors, any environmental factors like poor weather conditions can negatively affect their productivity (Florez et al., 2014). In masonry, these pressures persist (Boschman, van der Molen, Sluiter, & Frings-Dresen, 2011), perhaps in greater quantity and quality, especially if we consider the fact that masons can be expected to lay on average 1000 bricks per day (Grimm, 1975; Schneider & Susi, 1994). Furthermore, foremen, superintendents, and other managers are also under pressure from working long hours and task disruptions (Boschman et al., 2011).

1.2.1.2 Task Management

Certain masonry design elements and management issues can also affect the productivity of mason crews, including excessive block cutting, unit details, access, openings and wall sizes (Hassanein & Melin, 1997; Sanders & Thomas, 1991). Complex walls can already require more time and effort than simpler, standard masonry walls, but masonry unit sizes, wall shapes, and scope diversity can further increase the work time. Performance is also affected by the availability of materials, organization of the site laydown and storage areas, off-schedule work, and rework (H. R. Thomas & Završki, 1999). The mason subcontractor assigns work to the crews based on site conditions, other building systems, and available areas. This means that masonry construction is subject to the efforts of other trades such as mechanical, electrical, and plumbing (MEP), and will often have to wait for an area to be finished or ready for the mason subcontractor to begin work. Upon completion of construction in a particular area, crews can be reconfigured with different skills to balance quality and productivity. The crews could be organized to pair similar skills (e.g. the most experienced workers in one team and less experienced workers in another), to complement different skills (e.g. more skilled masons paired with less experienced laborers), to group compatible behaviors, to match skills with related tasks, or just indifferently. Therefore, it is crucial for supervisors to be aware of tasks, activities, conditions, and workers' skills (Florez et al., 2014).

1.3 The Path Forward

Other sectors and industries have been met with similar concerns and have found solutions or are currently working to rectify any problems. Even in the construction industry, we've seen improvement in the performance of various trades. Much of this progress has come from technological and process innovation in those industries. For masonry construction, the problems can be addressed through similar means by employing key tools and methods of

evaluating the current state of the industry. In addition to taking cues from other areas of the industry, masonry construction needs to stay integrated and work with other stakeholders to improve productivity and efficiency (Shen et al., 2010).

CHAPTER 2

INFORMATION TECHNOLOGY AND PROCESS MODELING

Computers have revolutionized virtually every aspect of modern-day life. Industries that have adopted the power of computing tools and information technology (IT) into their business practices have benefited greatly in increased productivity, quality, and more (Black & Lynch, 2001; Davenport & Short, 2003). Furthermore, new practices like process modeling have led the way in analyzing industrial practices for greater improvements (Havey, 2005; R. P. Smith & Morrow, 1999; Tornberg, Jämsen, & Paranko, 2002). In previous decades, the construction industry has not fared as well as other industries (Teicholz, Goodrum, & Haas, 2001). Since supervisors in the construction industry can spend 75% to 90% of their time on communication and data handling (Fisher & Yin, 1992), it seems natural that the industry would move towards greater usage of these innovative tools. Such technology has already seen great return in the construction industry (Eastman & Sacks, 2008).

2.1 Building Information Modeling

In the architecture, engineering, and construction (AEC) industry, Building Information Modeling (BIM) has emerged as the leading development in IT and modeling (Azhar, 2011). BIM represents both a process and a model, i.e. Building Information Modeling and Building Information Model. The model is an accurate virtual representation of a building constructed digitally during the process containing key information that can be utilized for various purposes throughout a project life cycle including visualization, drawings, cost estimating, simulation, and facility management (CRC Construction Innovation, 2007). Although there is still room for further improvement, the benefits of BIM are clear and the potential is grand (Demian &

Walters, 2013). Though the concept is not new, BIM utilization varies across and within each branch of the AEC industry (Eastman, Teicholz, Sacks, & Liston, 2011; Gilligan & Kunz, 2007; Young, Jones, Bernstein, & Gudgel, 2008).

2.1.1 Building Information Modeling for Masonry

In the past decade, BIM has grown from a trend into an industry focus. Many leading firms have traded 2D methods for new BIM workflows (Eastman et al., 2011). From 2007 to 2012, BIM use in North America jumped from 28% to 71% (McGraw Hill Construction, 2014). However, the masonry industry does not reflect this trend and may lose competitiveness with other building materials and systems and find it difficult to collaborate in a BIM-enabled industry. In a survey of general contractors rating which trades have high BIM skills, only 23% selected concrete/mason subcontractors, placing those trades above only drywall/ceiling subcontractors. Furthermore, in the US and Canada, only 13% and 8% of general contractors, respectively, chose concrete/mason subcontractors among the top three for BIM proficiency (McGraw Hill Construction, 2014).

Although several factors could be responsible for the industry's slowness in adopting BIM, it is largely due to the lack of well-documented workflows and case studies from BIM implementations. Without these supporting insights, it can be hard for the industry to justify the investment needed in software development and stakeholder education. The Building Information Modeling for Masonry Initiative (BIM-M) is currently addressing this issue through multiple projects on various topics including masonry unit databases and masonry project workflows (Building Information Modeling for Masonry, 2015). The latter, partially discussed in this thesis, focuses on a Masonry BIM Benchmark which addresses the aforementioned issues by providing a standards-based framework and using it to model the state of the masonry industry in

order to form a value proposition for the implementation of BIM tools for masonry. With this foundation, BIM for masonry can be better incorporated into construction projects, developed further, and improve the competitiveness of masonry in the construction industry.

2.2 Process Modeling

Process modeling is used to describe and communicate the states of a system or process and the elements associated to the process. A process can refer to the handling of information, the running of a program, or to a certain procedure. In industry, process modeling can be used to depict the current and future processes of a certain practice or organization (Indulska, Green, Recker, & Rosemann, 2009). Although there are numerous software tools and languages used for process modeling, the entities and their purposes can relate to similar ideas across all languages and platforms for modeling. Not only can process modeling show the activities that occur in practice, but it should also represent the organization structure of processes (Curtis, Kellner, & Over, 1992; P. Green & Rosemann, 2000). By accessing key information on specific elements or activities in business and/or construction processes, stakeholders can benefit from understanding a model that links activities to actors to data (Dong & Chen, 2001; Lee et al., 2012). In other words, process modeling allows us to analyze something by following it step by step and considering any inputs and outputs and their relationships to one another. The products of process modeling can include a data tree of all relevant elements and various diagrams representing the various organizations and activities. Process modeling can improve strategy, organization, management, operations, and IT infrastructure (Shang & Seddon, 2002). Potential benefits include process improvement, understanding, visualization, communication, and knowledge (Indulska et al., 2009). Although it may not be fully realized yet, process modeling

has already been adopted by the construction and brought with it the benefits from related IT tools (Sacks, Eastman, & Lee, 2004).

2.2.1 Business Process Modeling

Business process modeling follows the same tenants as other information system and process modeling, but is specific to the design and execution of business processes (Havey, 2005). The Business Process Modeling Notation (BPMN) is a language designed to build diagrams of business processes using graphical representations. BPMN has five main categories of elements, which are show in Figure 1 (Stiehl, 2014):

1. Flow objects: activity, gateway, event
2. Data: data object, data input, data output, data store, message
3. Connecting objects: sequence flow, message flow, association, data association
4. Swimlanes: pools, (swim-) lanes
5. Artifacts: group, text annotation

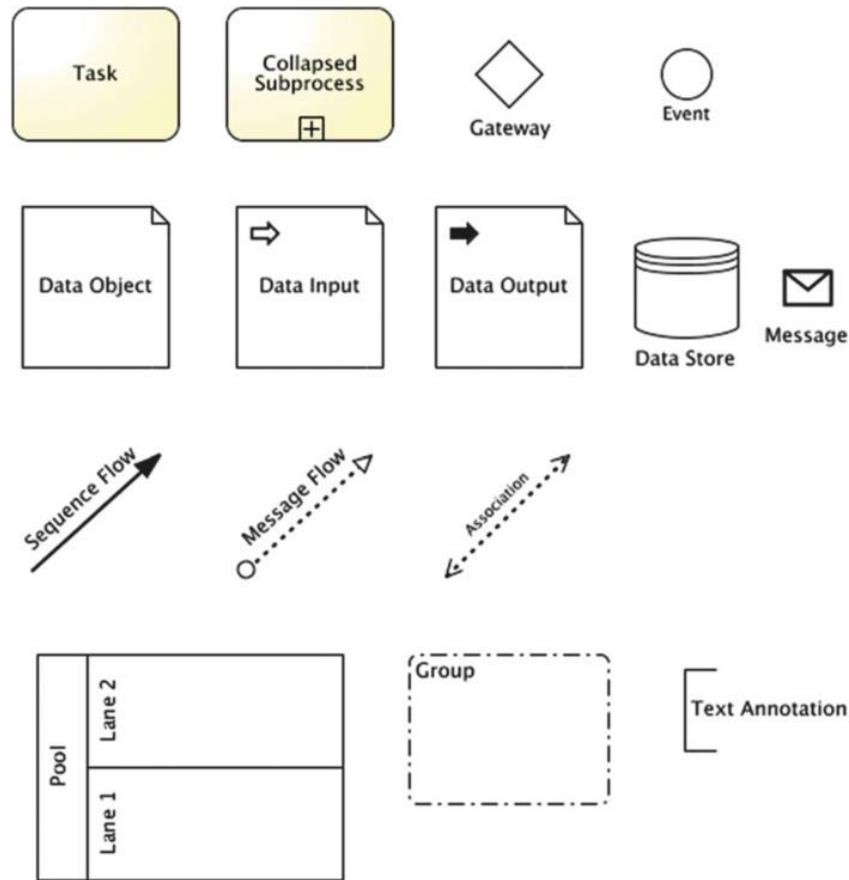


Figure 1 BPMN Elements

Although it has some useful aspects, including the swimlane representation of interconnected activities and data management, BPMN also has its pitfalls which may make it not the most ideal choice for implementation in all scenarios, especially in masonry construction. BPMN lacks formalization and relies on verbal descriptions in models, so it may be subject to interpretation and ambiguities. Also, BPMN does not support certain perspectives and data handling (Wohed, van der Aalst, Dumas, ter Hofstede, & Russell, 2006). This suggests that another process modeling language may be more fruitful for application and integration in masonry construction.

2.2.2 Systems Modeling

2.2.2.1 Model-Based Systems Engineering

When considering the needs of the masonry construction industry and BIM, it is clear that we need to address the entire system of a multidisciplinary industry. Systems engineering is a method to solve system issues catering to diverse stakeholder needs. Model-based systems engineering (MBSE) incorporates systems modeling to this process to support requirements, design, analysis, verification, and validation through all project phases (Friedenthal, Moore, & Steiner, 2012). The AEC industry and systems engineering practices are transitioning from using documents to using models like many other industries, so MBSE can offer significant benefits in quality, productivity, and risk assessment.

2.2.2.2 Systems Modeling Language

The Systems Modeling Language (SysML) is an emerging tool for model-based systems engineering which can be used for modeling a variety of systems, including industrial and business processes. The complex systems described by SysML can include hardware, software, data, personnel, procedures, facilities, and more. SysML can represent structure, behavior, constraints, allocations, and requirements (Friedenthal et al., 2012). SysML was derived from the Unified Modeling Language (UML), which is mostly used to model the structure and design of software systems (Object Management Group, 2014). SysML offers the advantage of earlier tools, like BPMN, in that it can represent processes, requirements and data.

SysML includes the following nine different diagrams (see Figure 2) (Friedenthal et al., 2012):

- Package diagram (pkg) represents the organization of the model
- Requirement diagram (req) represents the text-based requirements and their relationships
- Activity diagram (act) represents behavior according to inputs, outputs, and controls (Note: To avoid confusion, “activity diagram” will be written out in following mentions)

- Sequence diagram (sd) represents behavior according to the sequence of exchanges
- State machine (stm) diagram represents behavior according to transitions between states
- Use case diagram (uc) represents functionality
- Block definition diagram (bdd) represents structural elements and their composition and classification
- Internal block diagram (ibd) represents interconnections and interfaces between the parts of an element
- Parametric diagram (par) represents constraints on values

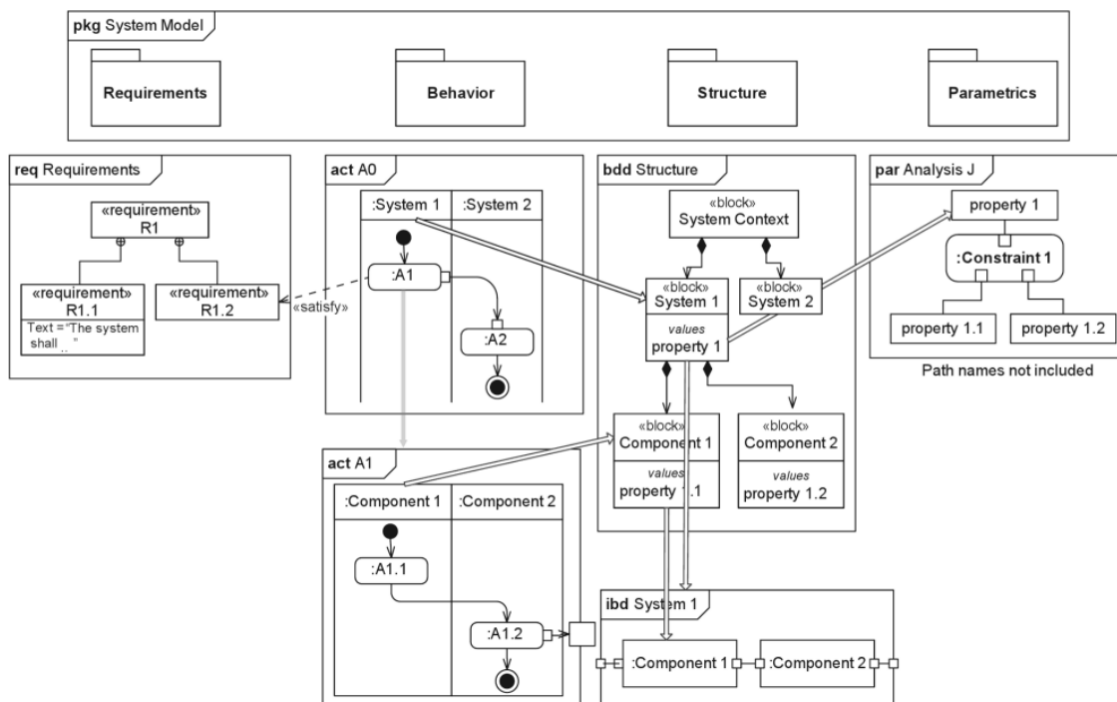


Figure 2 Simplified SysML Diagrams Showing Example Features

In this research, two main types of SysML diagrams were primarily used: the bdd and the activity diagram. The bdd shows the organizational structure of stakeholders, materials, information, and locations. The activity diagram shows the flow of actions and exchanges of

information. In a bdd, a block represents a general reference, like a title (e.g. “Superintendent”), and an instance block represents a specific reference, like a name (e.g. “John Smith”). In an activity diagram, a swim lane denotes which stakeholder performs the enclosed actions, and an object (central buffer) node represents any used objects, such as exchanged items, documents, or equipment. Blocks can have properties to specify values, parts, and more. Different types of arrows and lines are used to describe specific relationships between blocks. For this thesis, the software tool being used is MagicDraw and its SysML plugin (No Magic, 2015). Figure 3 shows a legend of SysML model elements in MagicDraw.

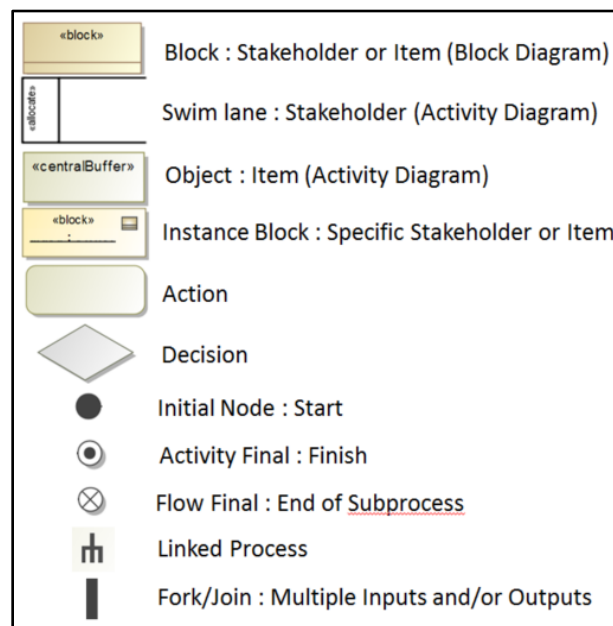


Figure 3 SysML Notation

Figure 4 shows a relevant example of how the SysML blocks are defined using three stakeholders on a typical construction project. The darker blocks are used to represent the generic stakeholders and their titles, i.e. “Owner,” “Architect,” and “General Contractor.” The lighter blocks represent the specific instances of those stakeholder blocks and display specific

names, i.e. “Georgia Tech,” “Cooper Carry,” and “McCarthy Building Companies,” respectively. Another way to distinguish between the two blocks is to use the conventional system of making the first letter lowercase for instance blocks. Figure 5 shows an example activity diagram of a simplified design process with a linked activity diagram (see Figure 6). The “Example Activity Diagram” starts off with the Owner making plans, after which the Architect creates the design for review by the Owner. The “Review Design” action links to another activity diagram which shows the more detailed interaction between the Owner and the Architect. The “Example Linked Activity Diagram” ends with the Owner beginning the bid process. Then, in the original “Activity Diagram,” the Owner receives the bid from and subsequently hires the General Contractor, who begins construction management.

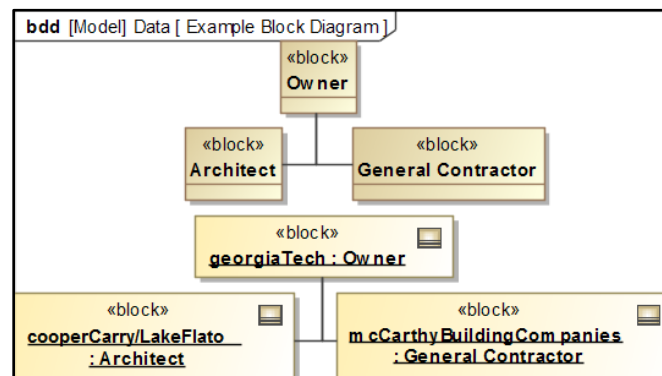


Figure 4 Example bdd with Blocks and Instance Blocks

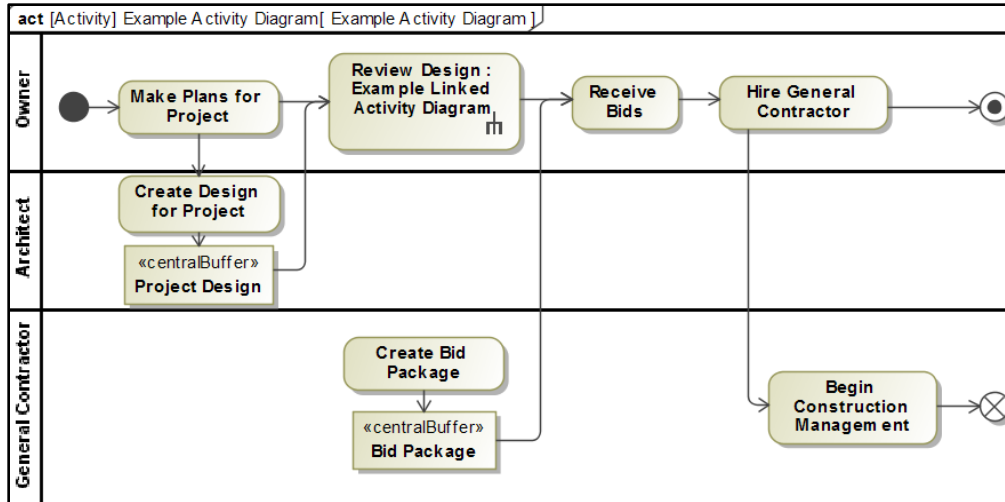


Figure 5 Example Activity Diagram with a Linked Activity Diagram

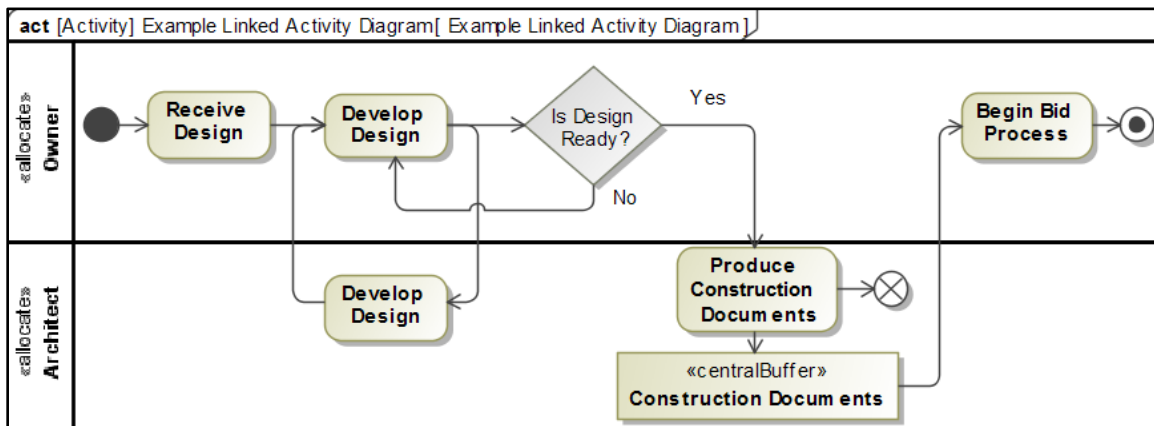


Figure 6 Example Linked Activity Diagram from Example Activity Diagram

Figures 7 and 8 show SysML examples of the design of a water distiller system (Friedenthal et al., 2012). The bdd in Figure 7 shows three blocks connected to “Distiller” via solid arrows with black diamonds. These relationships indicate that “Heat Exchanger,” “Boiler,” and “Valve” are parts of “Distiller” and cannot exist without it. Each block has ports indicating the inputs and outputs needed for those blocks.

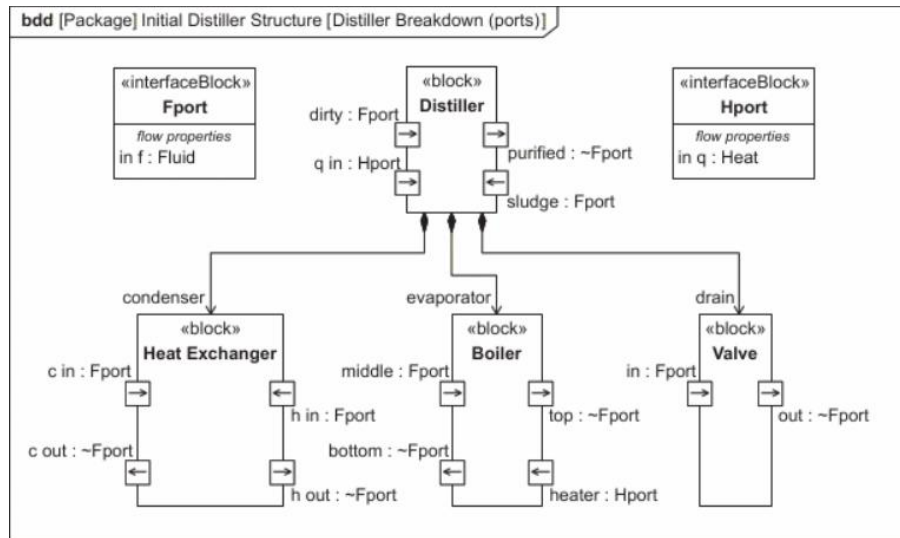


Figure 7 Example SysML bdd of Water Distiller System

The activity diagram (Figure 8) makes use of swimlanes to associate actions to the relevant blocks. The activity diagram has overall inputs and output as dirty and pure “H2O” and heat and residue. The arrows show the relationship of action and blocks as control and object flows. Although the distiller example does not display chronology the same way BPMN does, we can still trace the steps in the activity and imagine how it would appear similar to the SysML examples above.

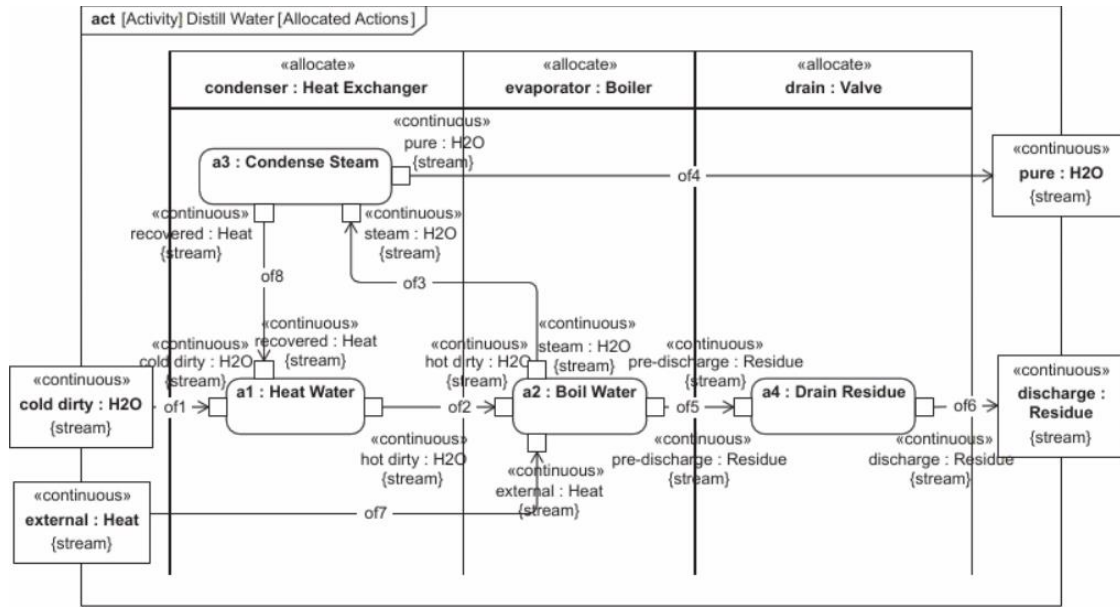


Figure 8 Example SysML Activity Diagram of Water Distiller System

2.3 Implementation of Tools

As seen in the previous examples, SysML can accurately and comprehensively describe a system or a process, be it in construction or a different industry. Although IT tools can be very valuable in alleviating problems in the construction industry, particularly masonry, we must still be mindful of how we integrate these tools into industry practices. Simply using computers and software tools does not suffice, since the application and method of integration will greatly determine the outcome and resulting success (Black & Lynch, 2001; Melville, Kraemer, & Gurbaxani, 2004). Furthermore, finding a way to formalize the language used in the models will be crucial for proper integration with other tools or just for modeling the system (O. Thomas & Fellmann M.A, 2009). Whatever the tools being used are, the key is to utilize them smartly to eliminate waste and extract as much value as possible (Azhar, 2011; Korkmaz, Messner, Riley, & Magent, 2010). We need to be able to understand the who, what, when, where, why, and how of any process and determine how beneficial these tools can really be, since not every situation

requires the information in the same way or in the same amount (Friedenthal et al., 2012). This requires a deep understanding of the industry and its practices, since practitioners and researchers will probably view the problems and the tools differently from one another (Indulska et al., 2009)

CHAPTER 3

CASE STUDY METHODOLOGIES

3.1 Contextualist Research

In construction, many of the workers' skills are learned on the job, and for masonry construction, there are many trade specific details. Using traditional methods of research does not suffice for studying the interactions in the industry (S. Green, Kao, & Larsen, 2009). In the same way that working in the industry requires hands-on learning, conducting research also requires hands-on learning to truly understand the ins and outs of masonry construction (Phelps & Horman, 2009). Information gathered in this manner can help to identify the realities of a construction project through different perspectives and to understand the significance of their context (Ferne, Leiringer, & Thorpe, 2006; Pink, Tutt, Dainty, & Gibb, 2010).

3.2 Case Study Research

One way of conducting field-based research is through case studies. Case studies can offer project insights that may not be possible by other methods. Though some may doubt their efficacy, case studies can be a viable and valid research method, especially in an uncontrolled environment such as an outdoor construction site (McCutcheon & Meredith, 1993). In addition to research in other industries (Runeson & Höst, 2009), construction research has already benefited from case studies in measuring feasibility, strategy, performance, and more (Koo & Fischer, 2000; Stewart, Mohamed, & Daet, 2002; Yang, Wu, & Tsai, 2007)

3.3 Case Studies for Thesis Research

Similar to the implementation of BIM for other building systems, BIM for Masonry must first be addressed through the observation, documentation, and development of current industry

practices. The aforementioned BIM-M Benchmark project is designed to achieve this goal using several case studies of masonry construction projects. A goal of the case studies is to identify how stakeholders are executing the various processes, workflows, and exchanges related to masonry construction, with or without BIM, throughout the main construction phases involving contractors and subcontractors.

This thesis is based on the knowledge gathered from the several case studies that were conducted in the summer and fall of 2014. The first case study was started in the summer and the rest were completed in a course taught in the fall at the Georgia Institute of Technology (Georgia Tech), BC 6550 Design and Construction Processes. The class of twenty-six graduate students from the Schools of Architecture, Building Construction, and Civil Engineering was organized into seven teams to conduct case studies of six completed masonry construction projects and to continue the one started in the summer (see Table 1). An eighth case study is being conducted by a research team at the University of Pennsylvania.

Table 1 Masonry Project Case Studies

Case Study	Project	Architect	Mason Subcontractor	Building Type
1	GT Engineered Biosystems Building	Cooper Carry	Jollay Masonry	Concrete Frame - Brick Veneer on Steel Studs - Interior CMU
2	Emory/Oxford Fleming Hall	Cooper Carry	Pyramid Masonry	Load Bearing Block - Precast Plank, Brick/Stone Exterior
3	Drew Charter School, Senior Academy	Perkins + Will	Cornerstone Masonry	Concrete Frame - Field Stone and Cast Stone over CMU
4	Woodward Academy Humanities Building	Perkins + Will	Cornerstone Masonry	Steel Frame - Brick and Cast Stone on Steel Stud Backup
5	Breckinridge Place	Holt Architects	Dave Trayer Masonry	Load Bearing Block - Precast Plank, Brick/Cast Stone Exterior
6	GCSU Ennis Hall + GT Hinman Hall	Lord Aeck Sargent	Southeastern Restorations	Load Bearing Brick and Stone - Restoration
7	Young Harris, Enotah Hall	Lord Aeck Sargent	Zebra Construction	Load Bearing Block - Precast Plank, Brick Exterior
8	UPenn, Huntsman Hall	KPF	Dan Lepore and Sons	Complex Masonry, Custom Clay Units, Concrete Frame

These projects included brick, CMU, and cast-stone masonry. The students were asked to conduct a comprehensive case study of their projects that would involve the use of SysML diagrams. The case studies were organized by the same criteria described in previous reports of the BIM-M Benchmark Project (Gentry, Eastman, Haymaker, & Lee, 2014). The criteria includes five project phases (Schematic Design, Design Development, Construction Documents, Contractor Coordination, Subcontractor Installation), three masonry types (Brick and CMU, Structural Masonry, Complex Masonry), and three states (Current No-BIM, Current BIM, Future BIM). The three states represent the states of BIM implementation on the project. “Current No-

BIM” means little to no BIM technology was used on the project, “Current BIM” means that some significant amount of BIM technologies was used, and “Future BIM” refers to use that moves towards full BIM implementation.

Figure 9 shows a visualization guide for understanding the aforementioned criteria: three masonry project types, five project phases, and three states of BIM implementation. These three, five, and three criteria can be imagined as a 3 x 5 x 3 three-dimensional (3D) matrix containing a total of 45 cells. Each cubic cell represents a specific project phase of a specific masonry project type of a specific BIM implementation. The idea is to populate this 3D graph with specific examples from case studies in order to produce a comprehensive map of the BIM-M criteria.

The research that has been done so far and is discussed in this thesis mostly comprises the Contractor Coordination and Subcontractor Installation phases, the CMU and Brick and Structural Masonry types, and the Current No-BIM to Current BIM states.

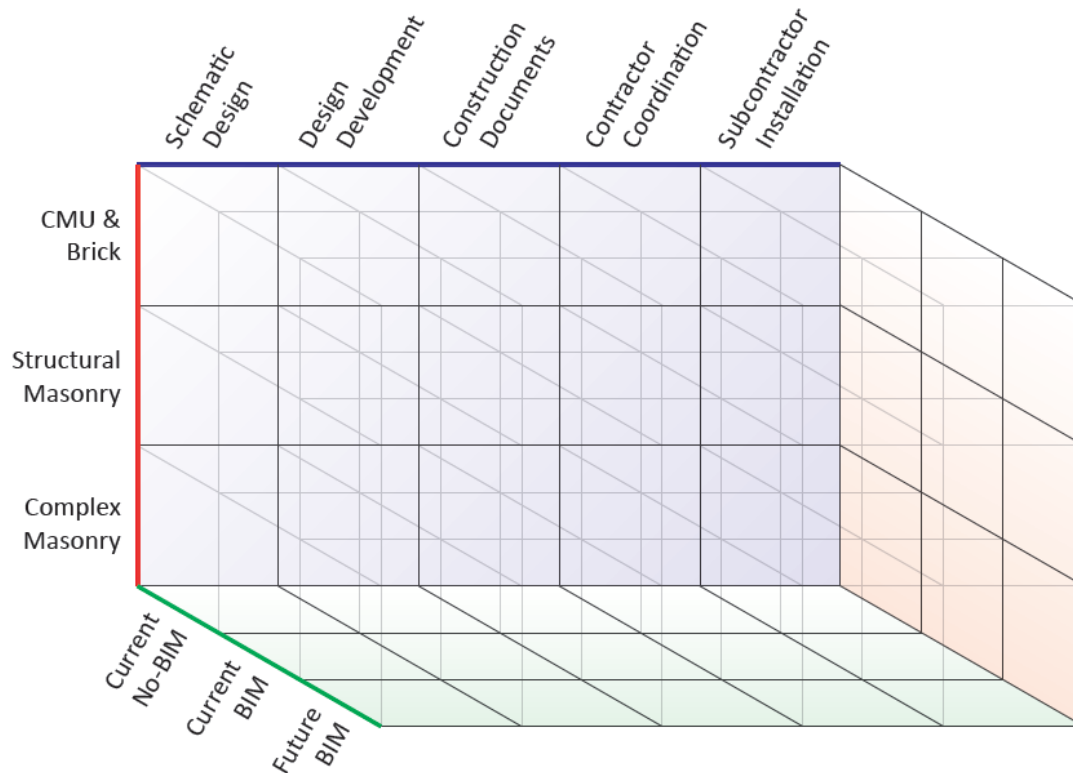


Figure 9 Visualization for BIM-M Benchmark Case Study Criteria

These case studies aim to identify the potential future state of BIM in the masonry industry. BIM and other management tools have advanced many construction processes, and connected to various modeling software and construction industry databases. By utilizing SysML diagrams, we can work towards developing BIM for masonry. Furthermore, integrating this research with a database such as BIM-M's Masonry Unit Database will improve BIM implementation and overall industry efficiency (Building Information Modeling for Masonry, 2015). The following chapters discuss a few key case studies and the lessons learned from them.

CHAPTER 4

ENGINEERED BIOSYSTEMS BUILDING

4.1 Project Background and Case Study Process

The Engineered Biosystems Building (EBB) is a project that is currently finishing up on the campus of the Georgia Institute of Technology. The \$113 million facility provides 220,000 square feet of collaborative space for interdisciplinary biomedical research (Lake|Flato Architects, 2014). The project delivery method was Construction Management at Risk, but there was a push for collaboration and implementation of Interdisciplinary Project Delivery (IPD) principles by the owner, as part of its new initiative for BIM implementation on all new campus construction projects. The structural style for the EBB is a typical cast-in-place reinforced concrete frame of columns and beams. The mason subcontractor's scope on this project includes brick on a façade, CMU in the basement, and cast-stone in certain areas of the facade.

Meetings with project stakeholders were held on- and offsite and masonry installations were observed throughout the construction process. The stakeholders and their responses were analyzed to determine the following:

- What information they require, from whom, and in what form
- How they process the information
- If the information is machine readable and convertible
- How they format the information for their own and others' use
- If their downstream users require models
- How the models are being used
- If anyone uses digital tools to simplify their work without being required by contract

4.2 Project Stakeholders

The project stakeholders of the EBB are shown in Figure 10 below. The owner is comprised of a few different entities, but for our purposes will be referred to as “Georgia Tech,” since it is the most recognized and the related owner parties usually act through the institution. The GC/CM is McCarthy Building Companies, Inc., the architect is comprised of the Cooper Carry, Inc. and Lake|Flato, and the mason subcontractor is Jollay Masonry, Inc.

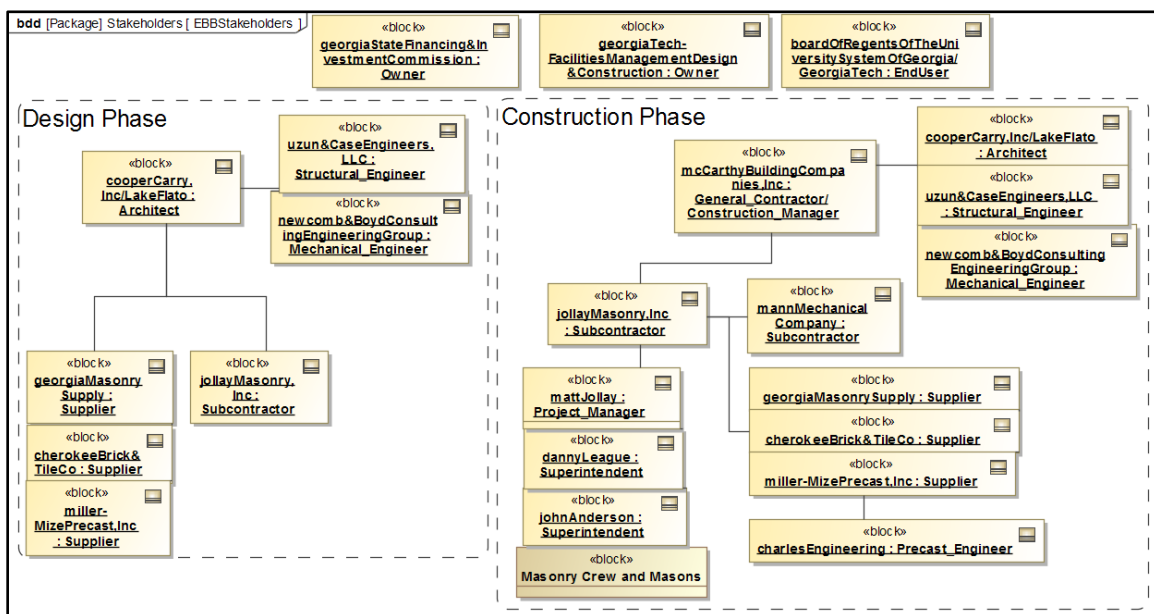


Figure 10 EBB Project Stakeholders

4.3 Masonry Scope

For the EBB, the masonry scope includes CMU, brick, and cast-stone (see Figure 11). The types of CMU blocks applied in the basement range from 4-inch (100 mm) to 8-inch (200 mm) solid bottom bond beam. The brick façade consists of both navy and gold glazed masonry provided through Georgia Masonry Supply and three types of mixed red clay brick – Tucker,

Mobile, and Natchez – from Cherokee Brick & Tile Company. Cast-stone is used in certain areas in the façade.

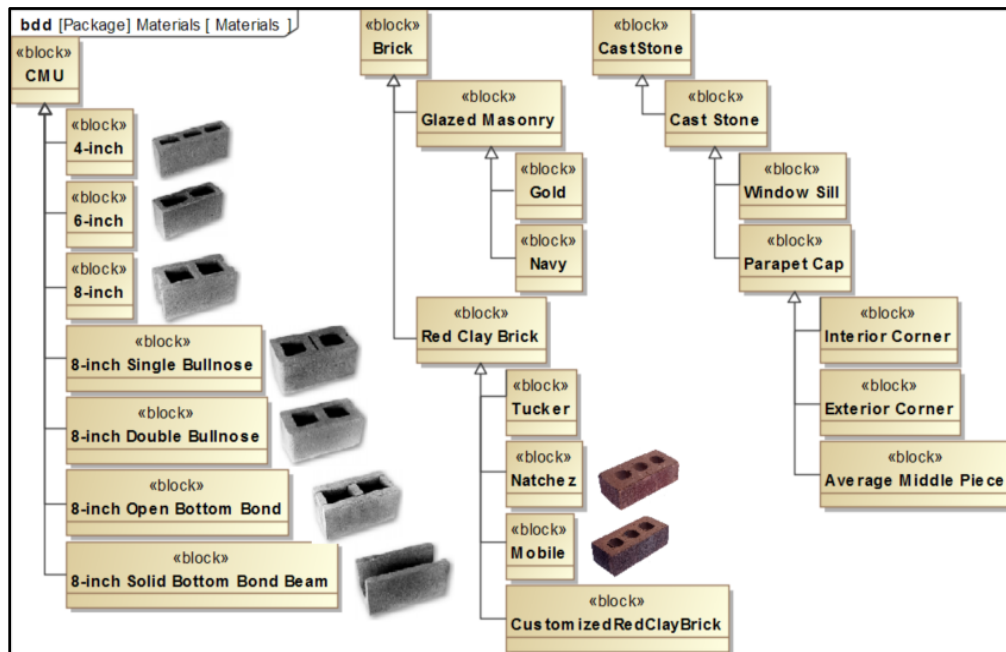


Figure 11 EBB Project Masonry Scope

4.4 Project Phases

4.4.1 Schematic Design Phase

In the Schematic Design phase, the owner, Georgia Tech, identified the project requirements. The design process primarily involved Georgia Tech and the architects, Cooper Carry and Lake|Flato. In this phase, the overall form of the EBB was established, and the building was mostly modeled in SketchUp. One important factor in the schematic design process was the selection of the architectural materials. In this project, five different small-scale mockups were used to develop the brick selection and pattern used on the building. Figure 12 shows the Schematic Design phase modeled with two main stakeholders. The “Select Architectural

Material” action node links to another activity diagram to further specify the marked action (see Figure 13).

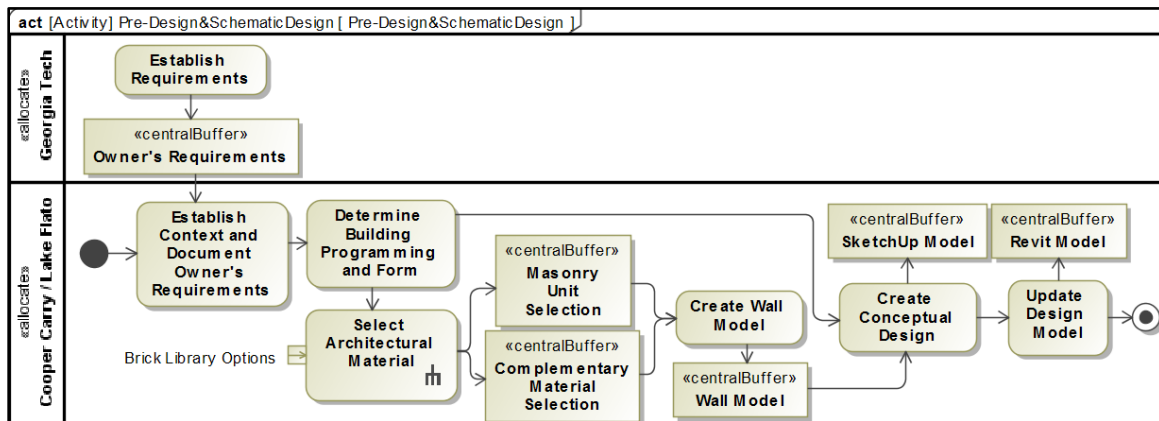


Figure 12 Schematic Design Phase

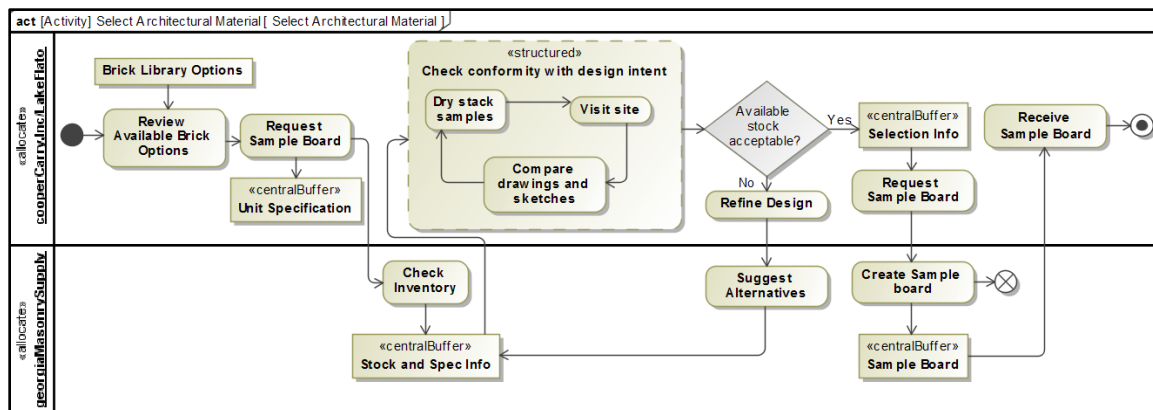


Figure 13 Select Architectural Material

In the Architectural Material Selection stage, the architects coordinated with the masonry suppliers to select the desired type, color, and number of bricks to be used on the façade of the EBB. This process involved multiple models which were created throughout the design phase. At first, dry stacking was done in the office and on site to properly identify which color patterns would be used. Later, a mortared mockup was created, and the mason subcontractor, Jollay

Masonry, provided the mockups at no additional charge to the architecture team. The “Check conformity with design intent” node represents a larger action that can be divided into more detailed, individual actions in the same diagram.

4.4.2 Design Development Phase

In the Design Development Phase, several factors of the initial design were tested with processes including energy modeling, structural modeling, and cost estimation. In this phase, the owner and architect worked closely together to fine-tune the design and models, while receiving input from various consultants. The models were developed beyond the aesthetic representations and constructed using BIM software, specifically Autodesk Revit. However, for masonry, these models are of relatively low quality, having a level of development (LOD) of roughly 300 and usually only showing a pattern applied to an extrusion.

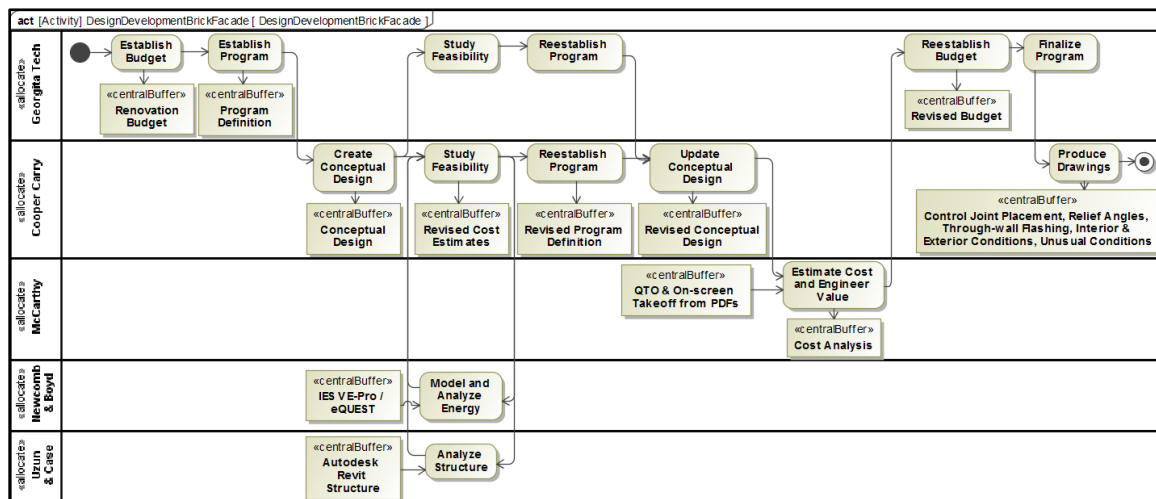


Figure 14 Design Development Phase

As shown in Figure 14, the Design Development Phase includes five swimlanes for the five main stakeholders involved in this process: the owner, the architects, the General Contractor/Construction Manager acting as estimator (McCarthy), the energy consultants

(Newcomb & Boyd), and the structural engineer (Uzun & Case). Several of the actions have object nodes below them which represent the specific documents or other phase deliverables that are produced from those actions.

4.4.3 Construction Documents Phase

In the Construction Documents Phase, the architects produced all of the architectural construction drawings and worked in conjunction with Jollay Masonry to produce the final masonry specifications (see Figure 15). At this stage, Jollay Masonry provided a critique and markup of the masonry details in the EBB – even before they were formally selected as the mason subcontractor for the project. The schedules were finalized, and the models and drawings were coordinated to correct any issues before construction.

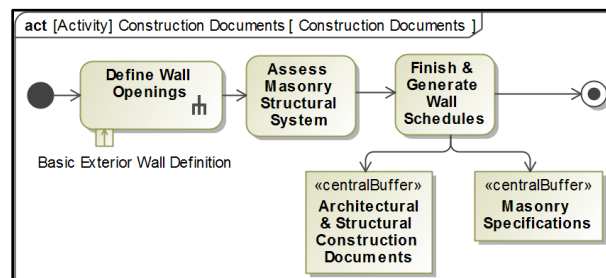


Figure 15 Construction Documents Phase

Although there was collaboration in this process, most of the construction documents were produced by the architects; therefore, this phase is represented using an activity diagram without swimlanes. The “Define Wall Openings” action node is expanded into its own diagram (see Figure 16).

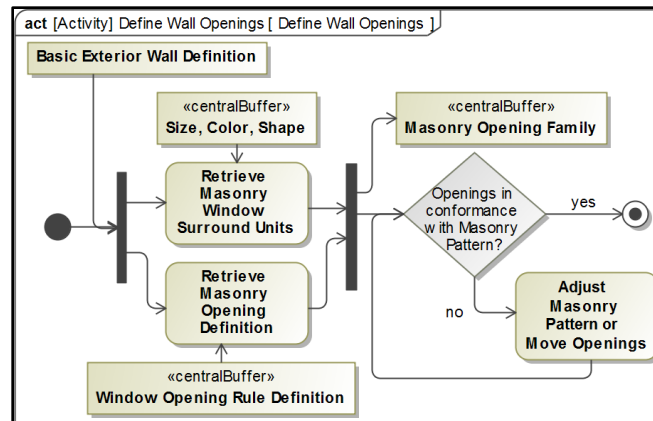


Figure 16 Define Wall Openings

In this process, the architects gathered all of the architectural and masonry specifications to produce detailed drawings of the various wall openings and special conditions. In this case, the architects checked whether or not the masonry wall openings were in conformity with the overall pattern. If they were, the activity ended; if not, the masonry design had to be adjusted and rechecked. However, these documents and drawings did not include all of the details that Jollay Masonry would require to satisfactorily complete their job. For example, Jollay Masonry had to create their own plan drawing of the basement level in which all of the locations of special installation conditions were marked with a color-coded key. Since some of the documents and drawings are outputs of the BIM models and software, it would seem highly beneficial to have smarter BIM tools and models that could easily extract the data that Jollay Masonry would need for such a drawing.

4.4.4 Contractor Coordination Phase

The Contractor Coordination Phase marks the beginning of the construction phase (see Figure 17). In this phase, McCarthy managed the construction of the entire facility while overseeing the operations of the various subcontractors onsite, including Jollay Masonry.

Although there were many more stakeholders involved with masonry in this phase, most of our

observations were of the interactions between the general contractor and the mason subcontractor, McCarthy and Jollay Masonry. In addition to onsite coordination, much of the interaction among stakeholders was done offsite through Requests for Information (RFI). Although Jollay Masonry may have initiated this flow of information, the official communication must be presented to the architects via McCarthy, and the formal exchanges were primarily done through the relaying of emails. This often resulted in Jollay Masonry having to wait days to weeks for an approved solution to an issue that could be resolved much quicker with a better platform and RFI process.

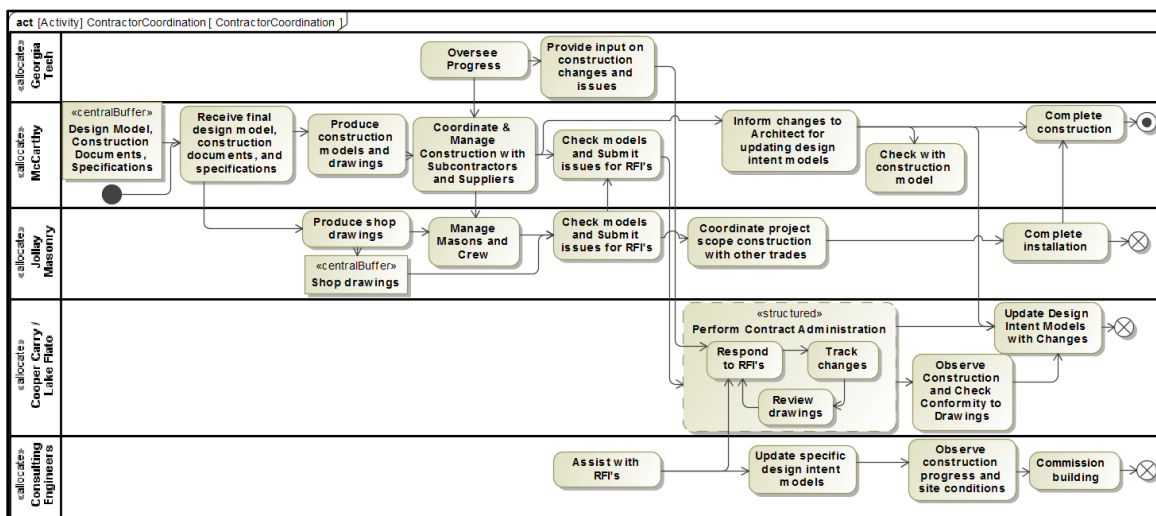


Figure 17 Contractor Coordination Phase

A more detailed iteration of the Contractor Coordination Phase involving RFIs in a cast stone workflow is shown in Figures 18 and 19 (Ranallo & Tarigopula, 2014). This activity diagram shows the information flows among the structural engineer, architect, GC/CM, mason subcontractor, masonry supplier, and precast engineer involved in the cast stone process.

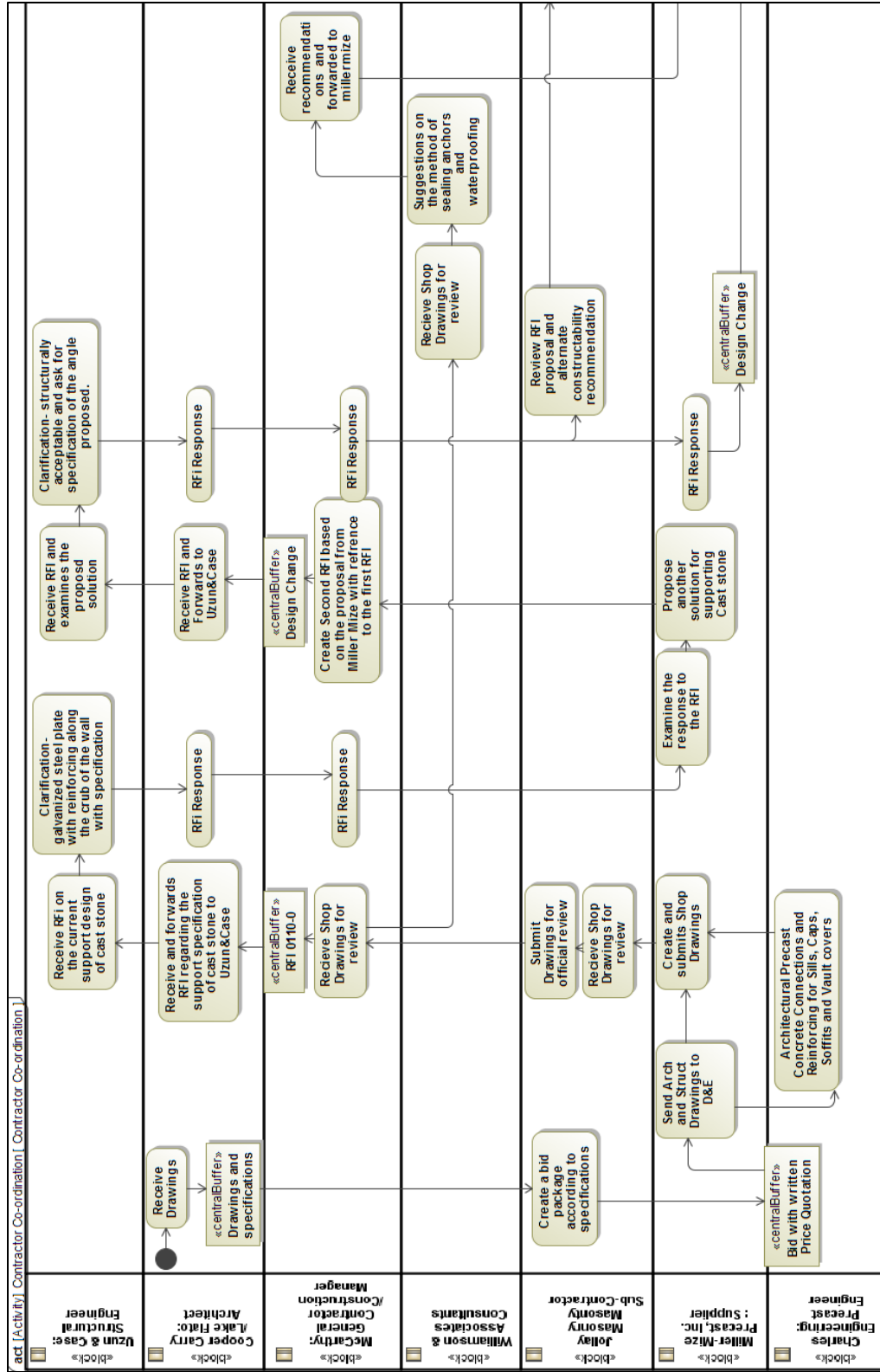


Figure 18 Contractor Coordination Cast Stone Workflow, Part A

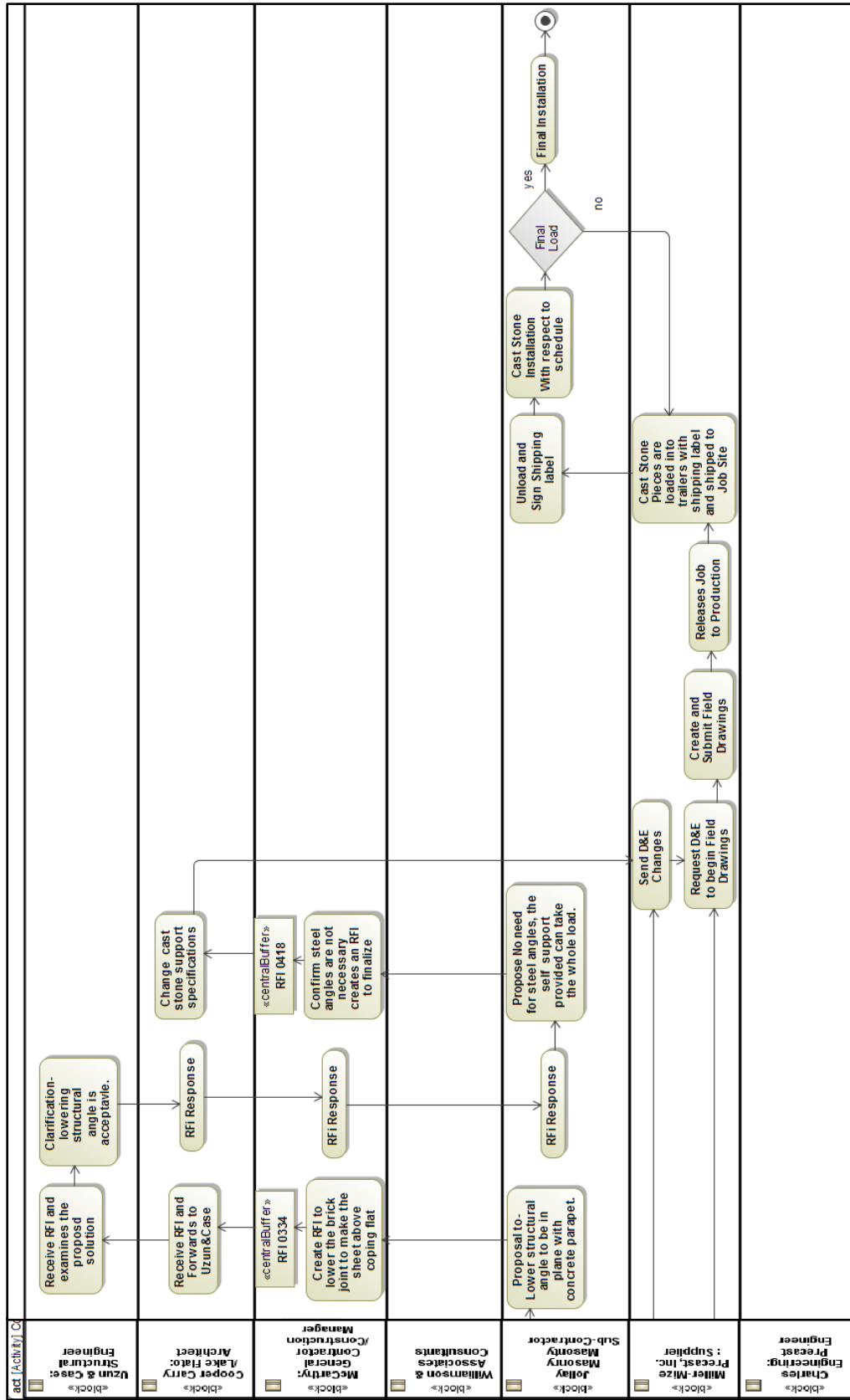


Figure 19 Contractor Coordination Cast Stone Workflow, Part B

4.4.5 Subcontractor Installation Phase

In the Subcontractor Installation Phase, Jollay Masonry coordinated with McCarthy to install the entire masonry scope of the EBB, which includes brick, CMU, and cast-stone.

Although BIM has rarely been used in traditional masonry jobs thus far, Jollay Masonry has made an effort to incorporate new technologies into its workflows. The two main types of installation covered in the following diagrams are the brick façade and basement CMU.

The brick façade consists of three types of red clay brick and two types of glazed masonry, navy and blue. The masonry project manager, Matt Jollay, handled most of the offsite coordination, while making the occasional site visit to consult with other project managers and contractors. The masonry superintendent, John Anderson, oversaw all of the brick work tasks onsite, including managing the masons and crew (see Figure 20). During the installation process both the masonry project manager and superintendent continuously reviewed the construction documents to properly coordinate the building teams and address any possible issues (see Figure 21). The brick façade installation phase ends with all stakeholders involved in the “Construct: Façade Construction” action, which signifies the daily repeated process of laying brick in one area. Figure 22 shows the expanded linked activity diagram of this action. Part of the process of observing brick façade construction involved visiting the site regularly twice a day for approximately 45 days. In addition to notes of the observations, photographs were taken of an entire area of the south wall to create a time-lapse of its construction from start to finish (Building Information Modeling for Masonry, 2014). These two groups of information provide an invaluable record of day-to-day operations which not only help to identify possible delays and problematic areas but also to influence the BIM implementations for these specific, detailed masonry workflows.

In the basement of the EBB, there is a vivarium, which will house many types of animals for research. This facility requires the use of CMU throughout the entire floor. This process involved significant coordinated labor among the masons and crew, which was managed by a second masonry superintendent, Danny League (see Figure 23).

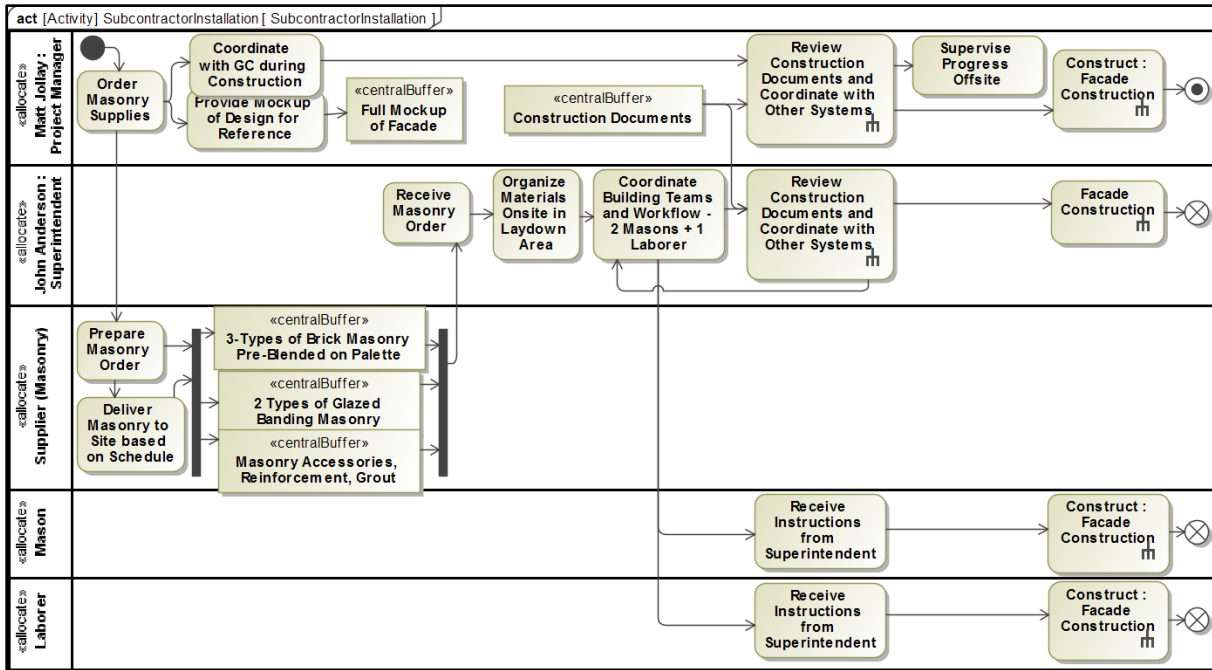


Figure 20 Subcontractor Installation Phase on Brick Façade

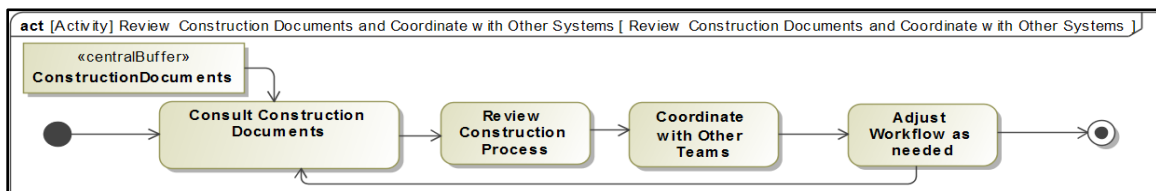


Figure 21 Review Construction Documents

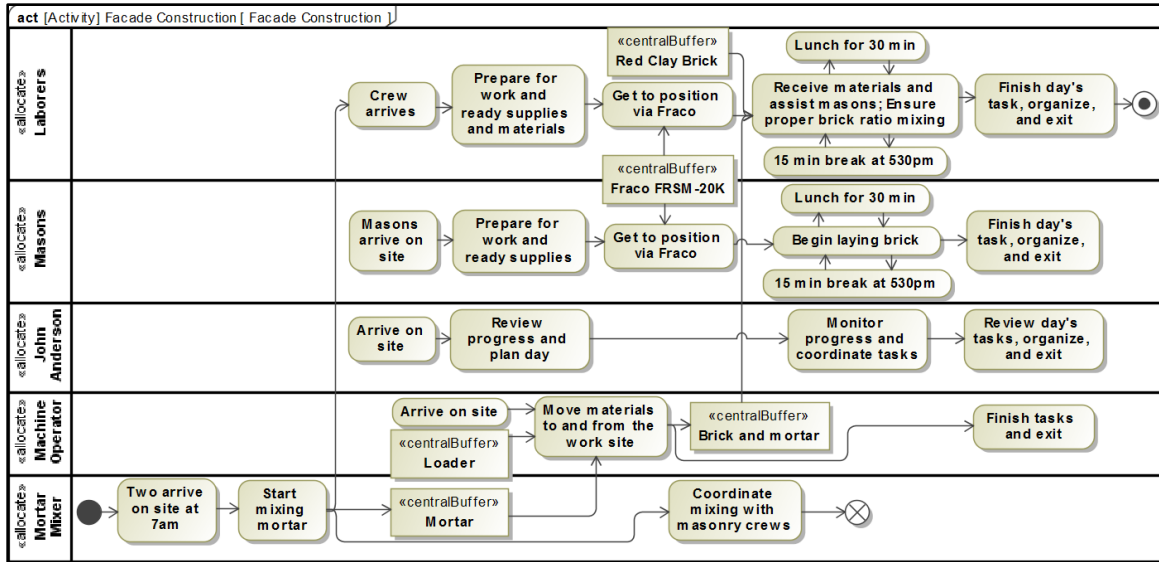


Figure 22 Façade Construction

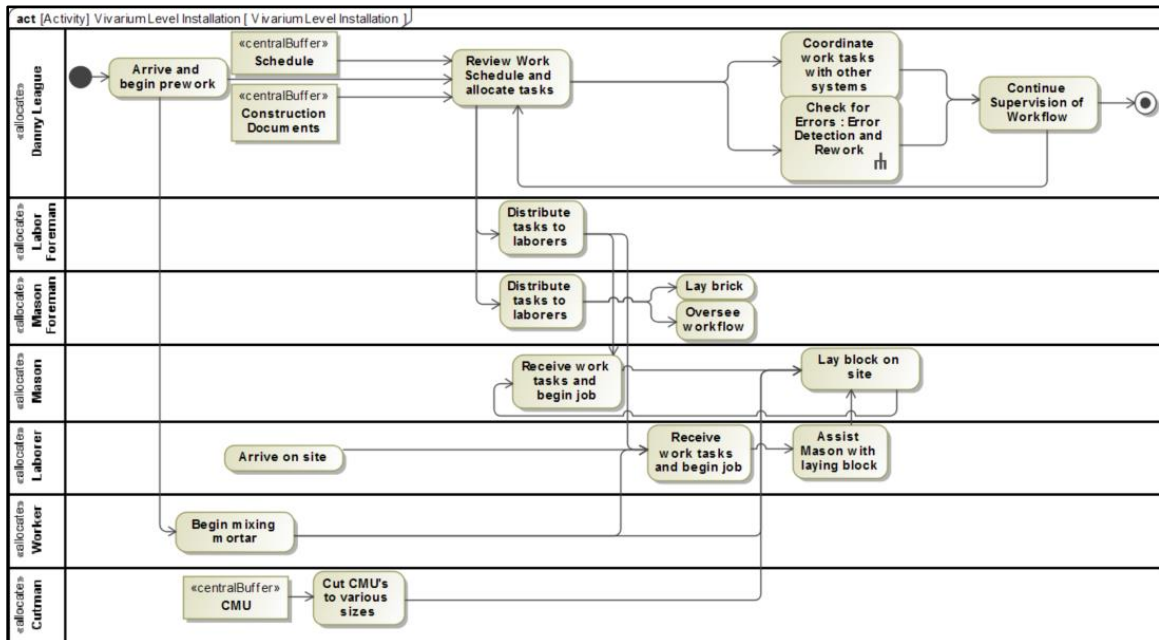


Figure 23 Subcontractor Installation on Vivarium Level

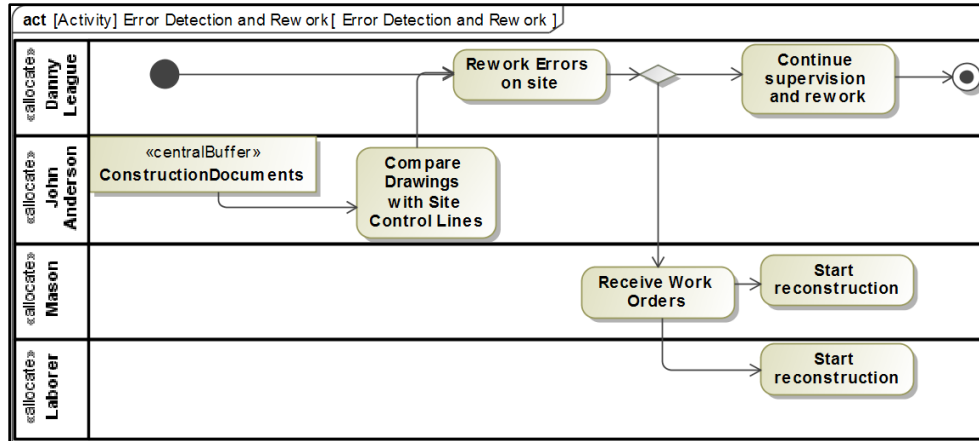


Figure 24 Error Detection and Rework

In Figure 24, the masonry superintendent, John Anderson, is reintroduced. In addition to acting as the superintendent for brickwork on the façade, Anderson conducted error checking to compare the construction documents to the actual layout of masonry structures onsite. If there were errors, those blocks and some walls needed to be demolished and reconstructed. In this case, a CMU wall that was constructed in the vivarium level was not in the correct location, according to the control lines off which construction was measured. After rechecking construction drawings and drawn control lines and considering the installation of other systems, such as MEP, the mason crews demolished and reconstructed the block wall.

In the case of the EBB, the re-measuring of the building frame and masonry substrate took approximately one man-month of superintendent labor. The errors identified and coordination required were communicated through a number of ad-hoc means – but none of this occurred through a BIM or even CAD-enabled process – and so this is considered “current state no-BIM”. In Figure 25, a selection of the type of coordination required is provided. Not all of these coordination issues were raised at EBB, but they are the most commonly encountered by the mason subcontractor. Most of this information involves the checking of existing building

geometry, and the communication of adjustments required before brick veneer installation can begin. In future BIM states, much of this communication can and should be made using BIM for masonry tools.

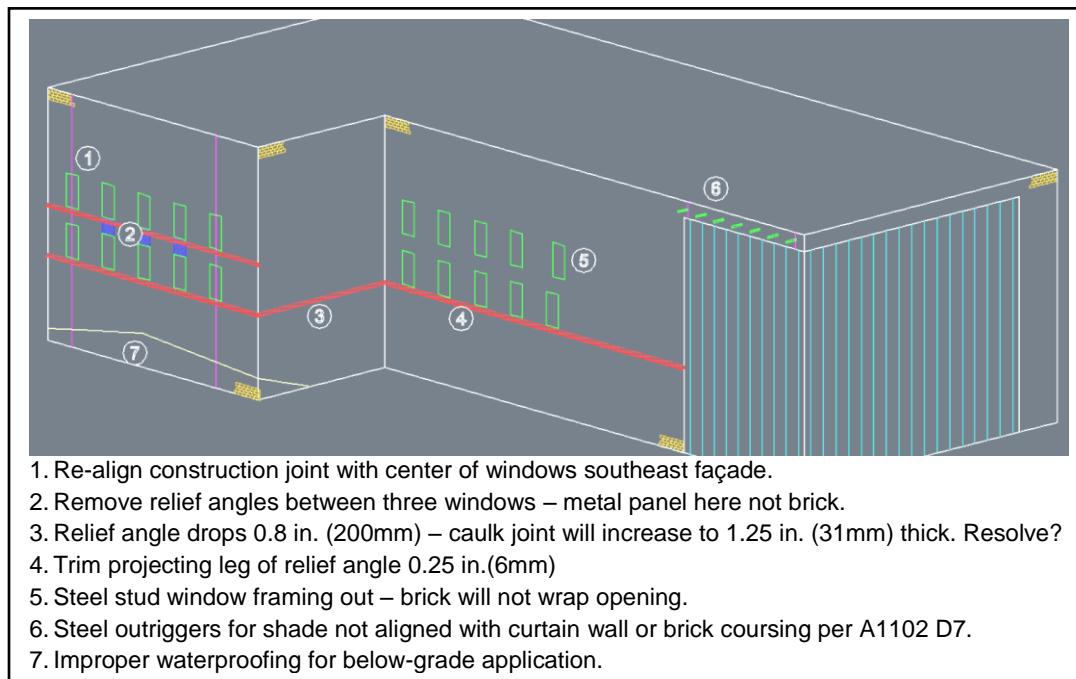


Figure 25 Example of Coordination Issues Required before Veneer Installation

4.5 Conclusion and Lessons Learned

The case study on the EBB provided a wealth of firsthand knowledge of the state of masonry construction. There were a few key points that presented opportunities for BIM tools and other tools to be adopted to improve the overall process. It was surprising that a mason subcontractor would need to invest an entire month of senior superintendent time to re-measure a building frame, before the start of masonry installation. This was on a BIM-enabled job where the GC/CM was laser scanning, updating BIM models, and more. Nevertheless, the building model did not sufficiently match the as-built geometry and the mason subcontractor felt they had

no option but to re-measure the building. In addition, the masonry superintendent did not have the digital tools to help transmit the re-measured information to the other building stakeholders that included the general contractor, the curtain wall installer, the concrete subcontractor, the waterproofing contractor, and the miscellaneous metals installer. Therefore, these communications were in the form of annotated photographs, hand sketches, memos, etc. Although Revit models were used on the EBB, these were mainly created for the use of the owner, the architect, and the GC/CM, and any model elements related to masonry were at a relatively low LOD. Bricks and blocks were essentially digital wallpapers on the surfaces of solids and there were intersecting clashes between the window sills and bricks throughout the model. These issues could be addressed by having a defined class of masonry units that could be used in BIM software. However, there is still a legal and logistical issue in terms of ownership of the models and who should be responsible for producing and maintaining them.

CHAPTER 5

ADDITIONAL MASONRY CASE STUDIES: FLEMING HALL, DREW CHARTER SCHOOL, WOODRUFF HALL

This chapter includes three different case studies conducted by student groups. Due to the different version of MagicDraw used and varied expertise in SysML among the students, some diagrams may appear different than the ones in the previous chapter. For proper SysML notation, please refer to the examples in Chapters 2 and 4.

5.1 Fleming Hall

5.1.1 Project Background

Fleming Hall is a 52,000 square-foot student residence hall on the campus of Oxford College of Emory University. The hall includes 106 traditional rooms, two study lounges, two laundry rooms, a large lobby, a tech lounge, a gym facility, and an outdoor terrace (Dermody, Ethayananth, Arul, & Li, 2014).

5.1.2 Project Stakeholders

Figure 26 shows the project stakeholders for Fleming Hall. The owner is Emory University, the architect was Cooper Carry, the GC/CM was Brasfield and Gorrie, and the mason subcontractor was Pyramid Masonry.

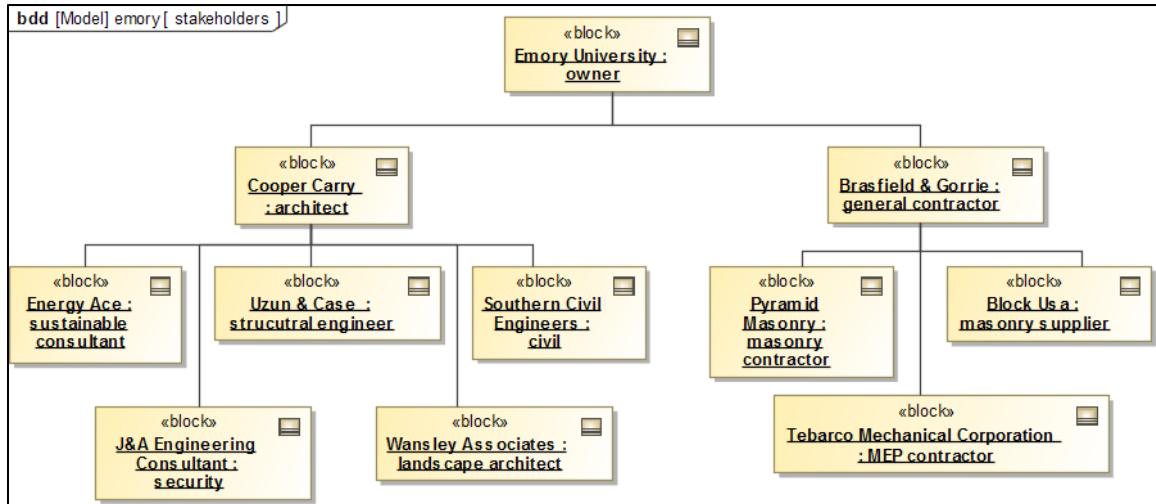


Figure 26 Fleming Hall Project Stakeholders

5.1.3 Project Masonry Scope

The masonry used on Fleming Hall includes CMU, brick, and granite, as seen in Figure 27. This bdd also includes some of the various accessories needed for masonry wall installation. The block strength and tensile strength are provided as value properties for a couple element blocks.

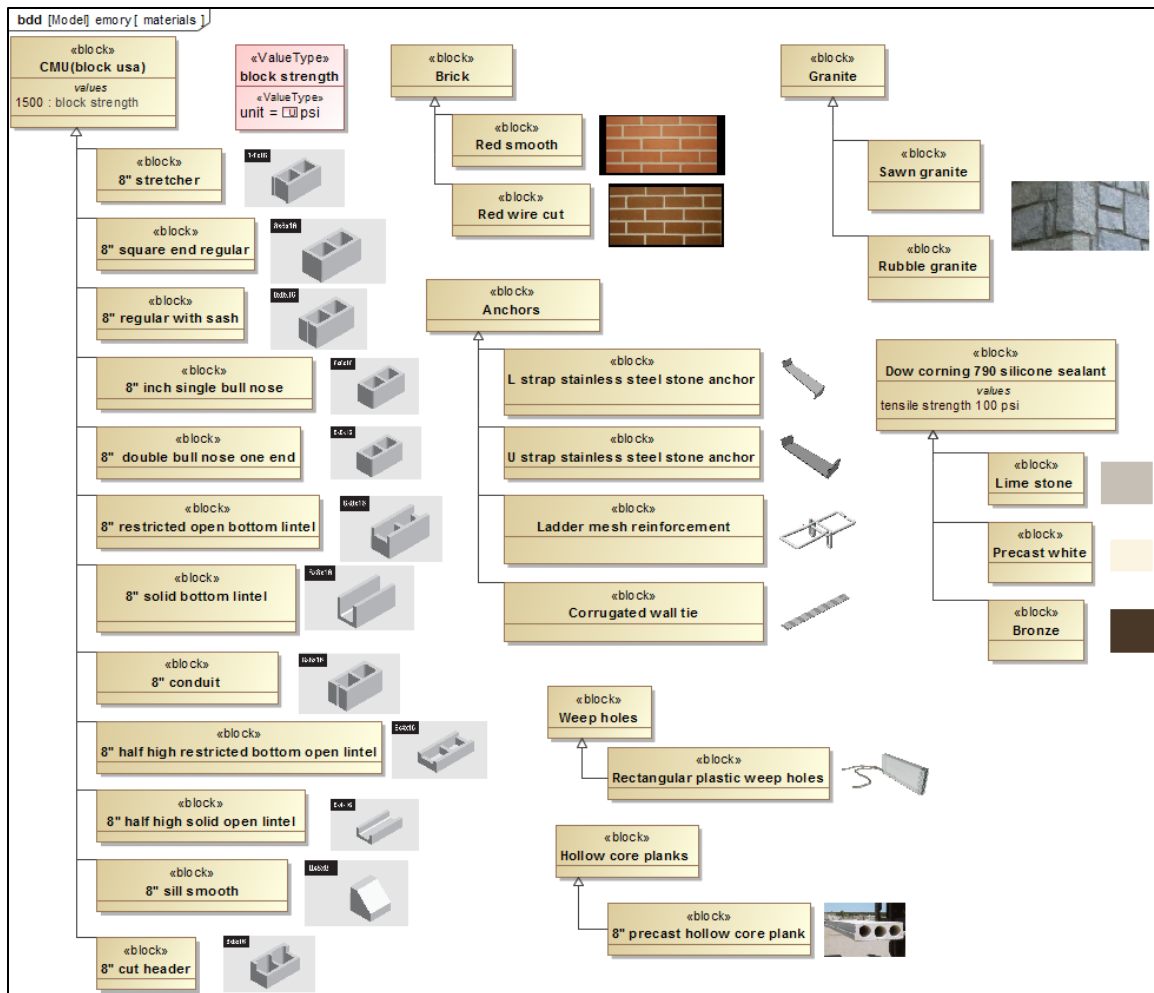
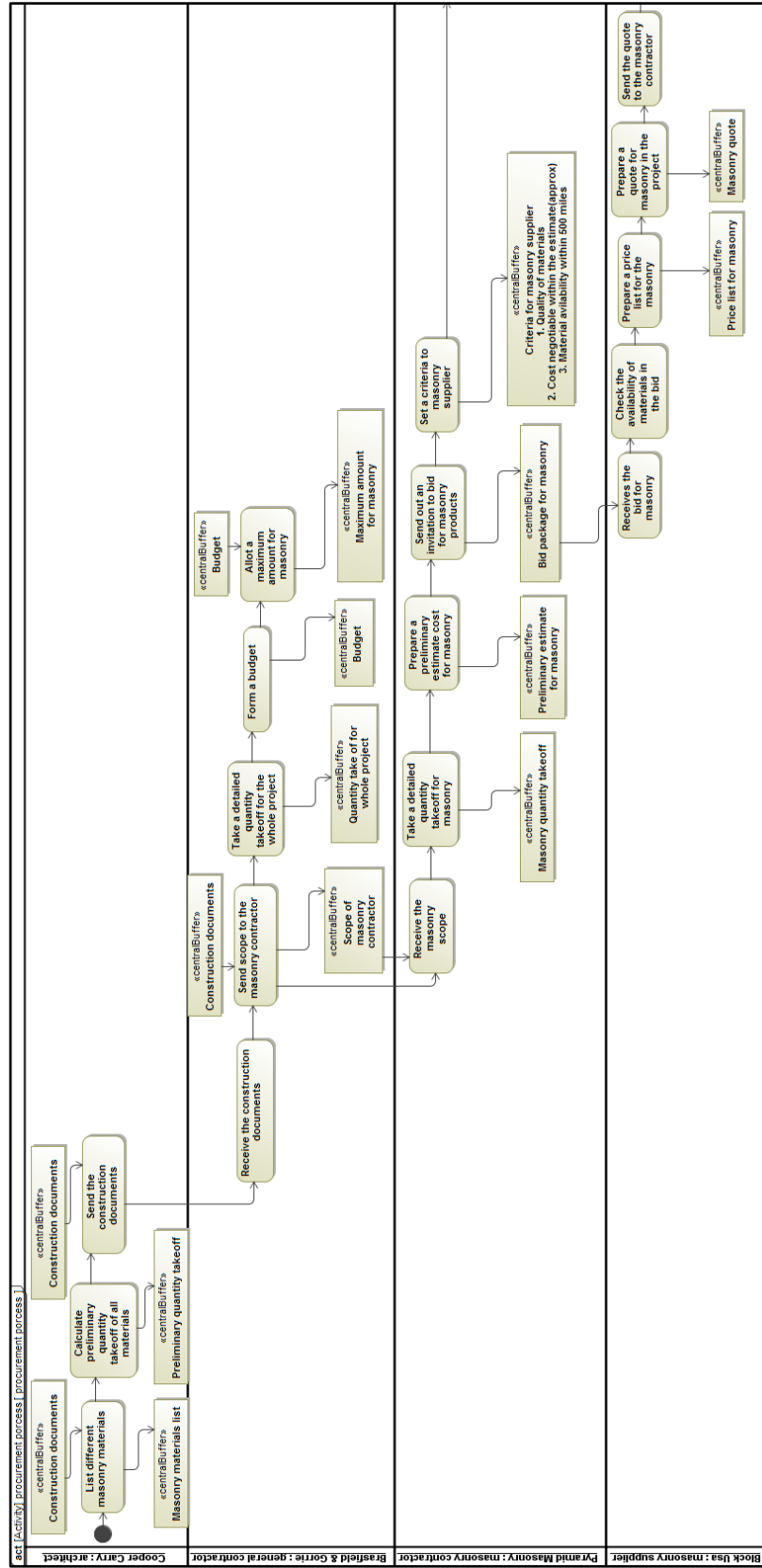


Figure 27 Fleming Hall Project Masonry Scope

5.1.4 Project Phases

5.1.4.1 Contractor Coordination: Material Procurement

Four stakeholders, the architect, the GC/CM, the mason subcontractor, and the masonry supplier, were involved in the material procurement process, as shown in Figures 28 and 29 (Dermody et al., 2014).



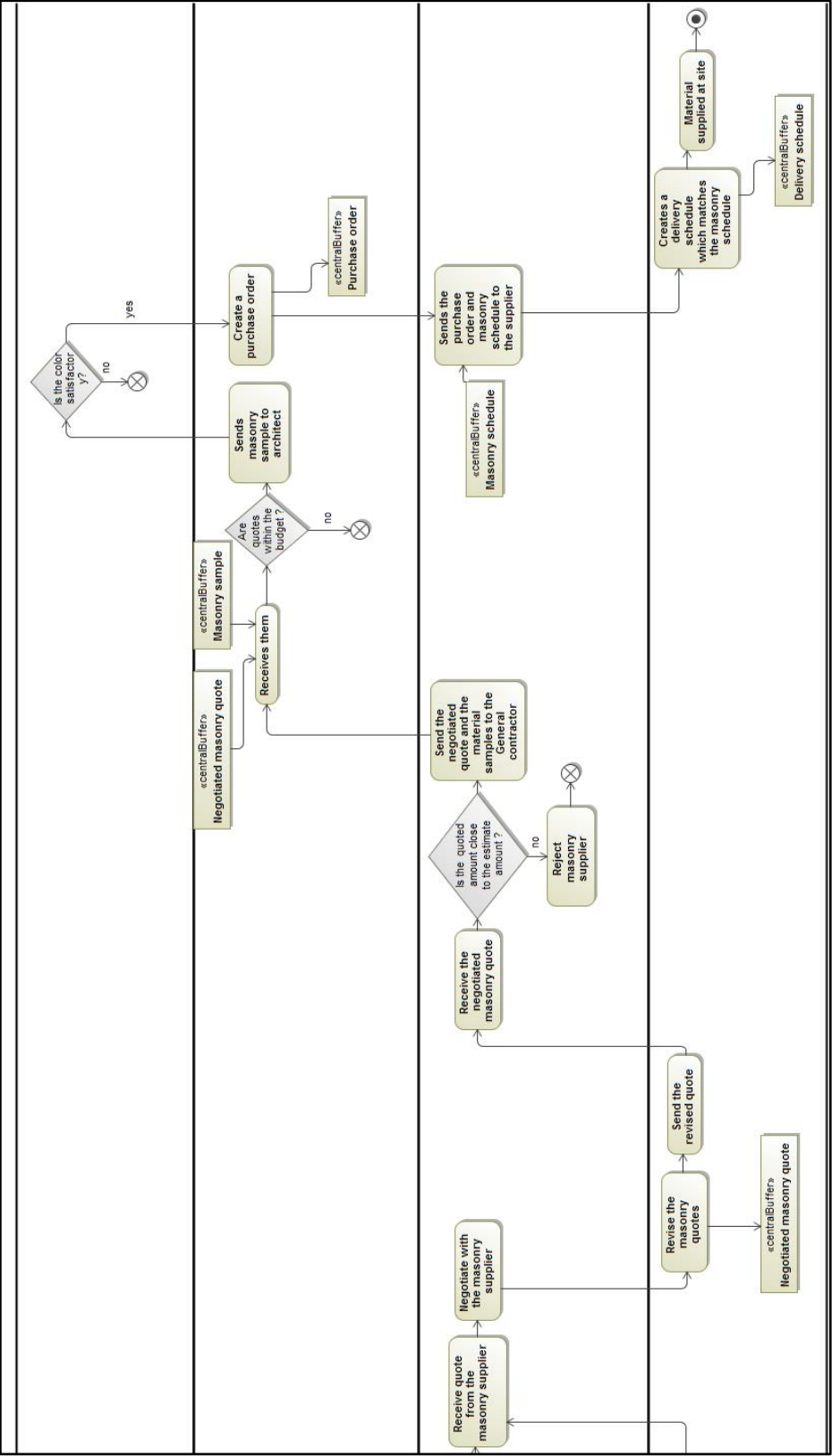


Figure 29 Fleming Hall Contractor Coordination Phase, Part B

We can see that in this material procurement process, the line of communication has to go from the architect to the GC/CM to the mason subcontractor to the masonry supplier. There is virtually no direct line of contact between the first stakeholder and the last.

5.1.5 Additional Case Study Measures

5.1.5.1 Stakeholder Concerns

Stakeholder interviews were also conducted during the case study process. The architect, structural engineer, and GC/CM were asked about their concerns during the construction of the project that could potentially make the process more efficient. The architect felt that better coordination was needed with the structural engineer on the various masonry wall openings, especially on the exterior, and that scheduling was the most difficult part of the installation. For the CMU walls, the structural engineer had to design the walls twice – once for gravity and “out-of-plane lateral loads” and again for gravity and shear wall forces, since the software (RAM Frame) could not model both. The general contractor had difficulty getting the right, qualified workers on the jobsite due to competition with another project being constructed at the same time, which resulted in regular quality issues and errors.

5.1.5.2 Subcontractor Installation Mockups

Before installing the masonry elements onsite, the subcontractor created mockups of the masonry to be installed. Table 2 shows the decisions made during this testing process (Dermody et al., 2014).

Table 2 Masonry Mockup Process

MATERIAL	ITEM
Brick	Confirmed revised dental brick detail (see 4/A5.01)
Cell Vent	Align cell vents at outside edges of window and have one centered in window opening
Cell Vent	Cell vents will be used on the project. Color chosen from samples was "dirty yellow"
Granite Banding	Granite pier to storefront condition: Decision made to stop banding short of storefront and run granite rubble instead so the vertical joint will be uniform along the entire edge of storefront. Decision also made to do this at granite pier to stucco conditions.
Granite Banding	Outward facing piece to be full width of face, have the mortar joint between pieces be on the side face(s) similar to a brick return
Granite Banding	Mortar joint directly above and below the granite band should be 1/2"-3/4" maximum
Granite Banding	Directly below granite cap - drawings show granite banding. Delete this band and have granite rubble extend directly under cap.
Granite Cap	Material confirmed. Team would like vertical height to be larger (6") and keep cap edges flush with rubble below.
Granite Cap	Vertical thickness of cap to be 6" and keep cap edges flush with rubble below
Granite Rubble	Bottom mortar joint of granite piers should be raked so carpet can slide in and not be cut
Granite Rubble	Avoid thin (width) pieces of rubble.
Granite Rubble	Maximum horizontal joint at non-band conditions to be 2/3 of the face

5.1.6 Conclusion and Lessons Learned

One of the main issues during the construction of Fleming Hall was the RFI processes and other communication being too inefficient and one-directional. The mason subcontractor would have to wait for an inquiry to go through multiple stakeholders to get to the architect and then come back with a reply. In addition to the communication process, better coordination is needed to improve construction productivity.

There were a few potential technological improvements or futures states that could be beneficial. First, the structural engineer's modeling software was not adequate and required a process to be executed twice. The GC/CM experienced some difficulty in hiring skilled laborers on the job. We can imagine that a SysML database with existing stakeholders could be populated with available laborers to help streamline the hiring process and select the best possible mason crews. Finally, there were several lessons learned from the physical mockups that were constructed in preparation of installation. With more advanced BIM and 3D modeling tools, virtual mockups may be able to make this testing process more efficient.

5.2 Drew Charter School

5.2.1 Project Background

The Drew Charter School is a 205,800 square-foot, two-story school building in the East Lake community of Atlanta, GA. This LEED Gold Certified building includes seven project learning labs and seven state-of-the-art science labs, a 500-seat performing arts center, and two gymnasiums, which serve approximately 1000 students in Pre-K to 9th grade (Ashrafi, Ginn, Lee, & McEwen, 2014).

5.2.2 Project Stakeholders

The major project stakeholders for the construction of the Drew Charter School are as follows:

- Architect: Perkins + Will
- General Contractor: JE Dunn Construction
- Structural Engineer: Uzun & Case
- MEP/FP Engineer: Newcomb and Boyd
- Civil Engineer: Pharr Engineering
- Mason Subcontractor: Cornerstone Masonry

- Field Stone Supplier: Weathered Tennessee Fieldstone
- Cast Stone Supplier: Corbelstone, Inc.

5.2.3 Project Masonry Scope

The school contains two major masonry materials: fieldstone and cast stone. Figure 30 below illustrates the location of the masonry details with the fieldstone in green and the cast stone in blue (Ashrafi et al., 2014). The fieldstone detail is predominately located on the south face of the building, while the majority of the cast stone is present on the north face where the two gymnasiums and auditorium are located. Neither of the masonry components of this project are load bearing.

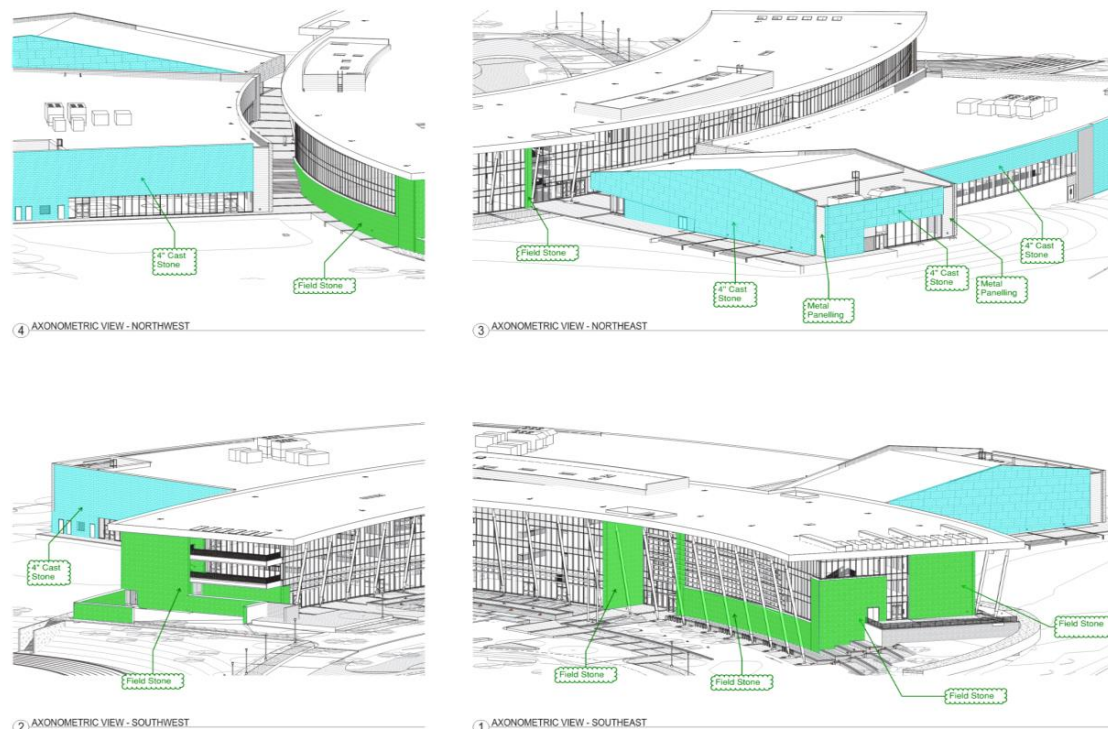


Figure 30 Location Breakdown of Masonry Materials

According to the architect, Perkins + Will, these two masonry materials were chosen in efforts to blend with the surrounding residential neighborhood in the East Lake community. The fieldstone provides a natural and weathered look while the cast stone provides a wood-like appearance that fits with the residential style.

5.2.4 Subcontractor Installation Phase

5.2.4.1 Field Stone Installation

In the fieldstone installation process, each rock must be chipped to fit a certain size and shape so that it fits perfectly adjacent to the surrounding stones and satisfies the determined pattern. This is a detail intensive and repetitive process that involves a great deal of coordination between masons, laborers, and stone cutters. The mason subcontractor used a 1.5:1 laborer to mason ratio for its crews in order to keep the process moving forward and prepare the appropriate stones. Figure 31 illustrates a linear overview of the major activities of the mason subcontractor while overseeing the installation of the field stone.

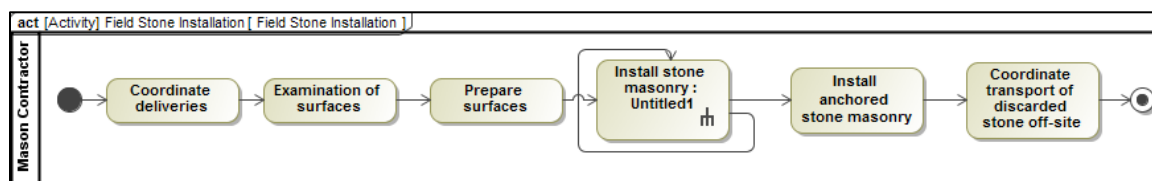


Figure 31 Drew Charter Subcontractor Installation Phase

The installation of the field stone is a highly repetitive process, so the action “Install stone masonry” is linked to another activity diagram to further describe the internal processes of the action (see Figure 32).

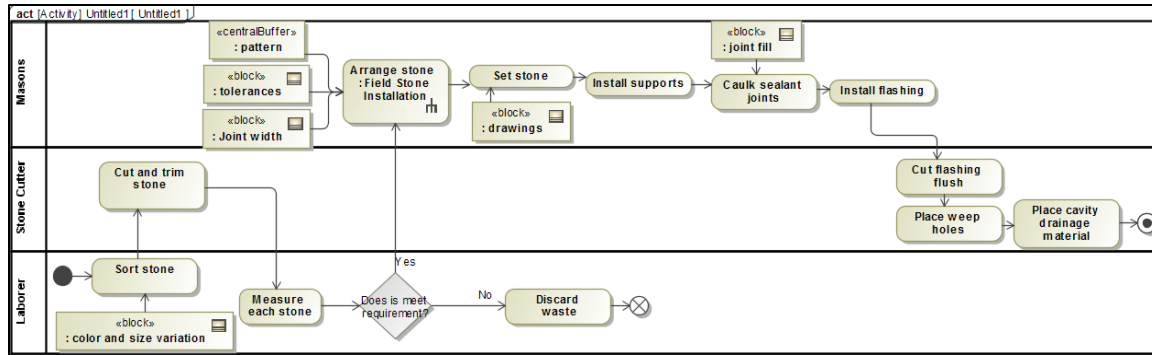


Figure 32 Install Stone Masonry

The bdd below (see Figure 33) represents the necessary inputs for the activity diagram above, based on the details in the project specifications.

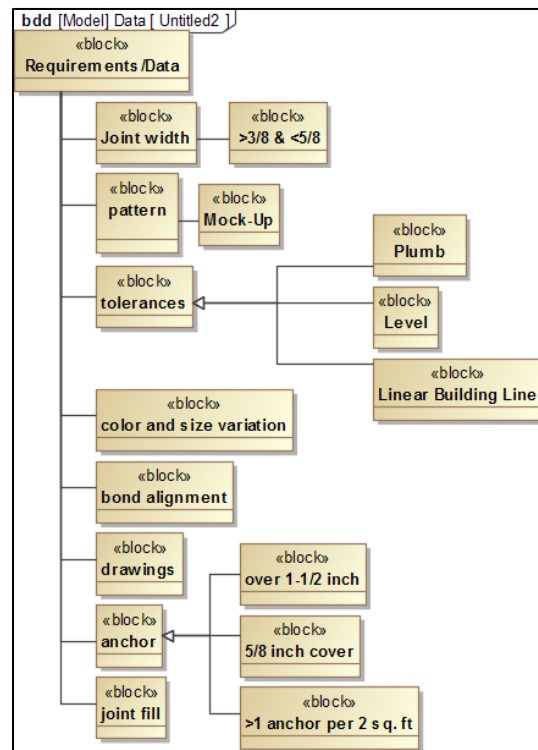


Figure 33 Data Inputs and Requirements for Fieldstone

The blocks shown in Figure 33 are used in the previous activity diagrams. Within the SysML file, all the data are connected so that we can review either specific inputs or actions and identify the other.

5.2.4.2 Cast Stone Installation

The auditorium at Drew Charter made interesting use of cast stone masonry. Due to the heavy and brittle nature of cast stone, the material must be handled and installed carefully and is not suitable for load-bearing purposes. On this project, the architect designed a large cantilevered and angled structure to be made of cast stone (see Figure 34).



Figure 34 Cast Stone Installation on Auditorium

The original design called for a 4'x8' block coursing for the wall. However, during the design development phase, after considering pricing, logistics, and constructability (one laborer can carry only one block), the mason subcontractor requested that the design be changed to a 4x4 coursing of 1'x2' blocks to mimic the 4'x8' appearance of the original design (see Figure 35).



Figure 35 Cast Stone Block Modification

Furthermore, several other factors, such as the angling and cantilever, required further customization and modification of the cast stone for installation (see Figure 36).

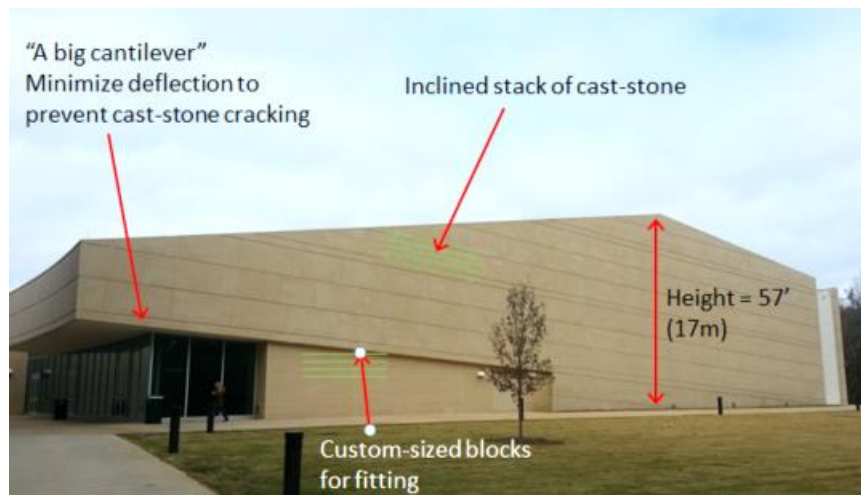


Figure 36 Cast Stone Wall Features

5.2.5 Conclusion and Lessons Learned

Although the Drew Charter School case study lacked the main criteria of the BIM-M Benchmark Project in terms of types of masonry, it still provided a unique problem pertaining to

masonry construction, namely in the cast stone workflow. As with many other masonry construction projects, one main design concept was to match the new construction with the surrounding buildings and neighborhood. In these cases, having access to a unit database of previously used and currently available masonry units would be beneficial in the initial design phase, especially when working with a highly customized material such as field stone and cast stone. Furthermore, although the color-coding in Figure 30 was done by the student team as an exercise, a similar or improved feature in BIM tools could prove useful for automatically populating masonry units in models or displaying key masonry scope information.

One of the main masonry construction issues in this project was the cast stone installation on the auditorium. Although the architect wanted a specific look of large cast stone features on the cantilevered wall, the mason subcontractor found it unfeasible and recommended a revised version to capture the same effect. Had the mason subcontractor been involved earlier on in the process, this decision could have been made a lot quicker with less iterations and rework.

Another factor in productivity was the fact that the architect always drew a design first, after which the GC/CM would create a cost estimate, which then received feedback from the mason subcontractor. Overall, a more interdisciplinary approach with connected databases would have seen great improvement on this project.

5.3 Woodruff Hall

5.3.1 Project Background

The Jane Woodruff Hall is a new building on the campus of Woodward Academy located in College Park, GA. This humanities building houses mostly language and social science classes. Similar to the other case studies, this project was in response to the growing number of

students, and the owner wanted to reflect the architectural narrative of the other buildings on campus with similar masonry finishes (do Amaral, Soundiah, Seenivasan, & Jia, 2014).

5.3.2 Project Stakeholders

Figure 37 below shows a bdd of the Woodruff Hall project stakeholders.

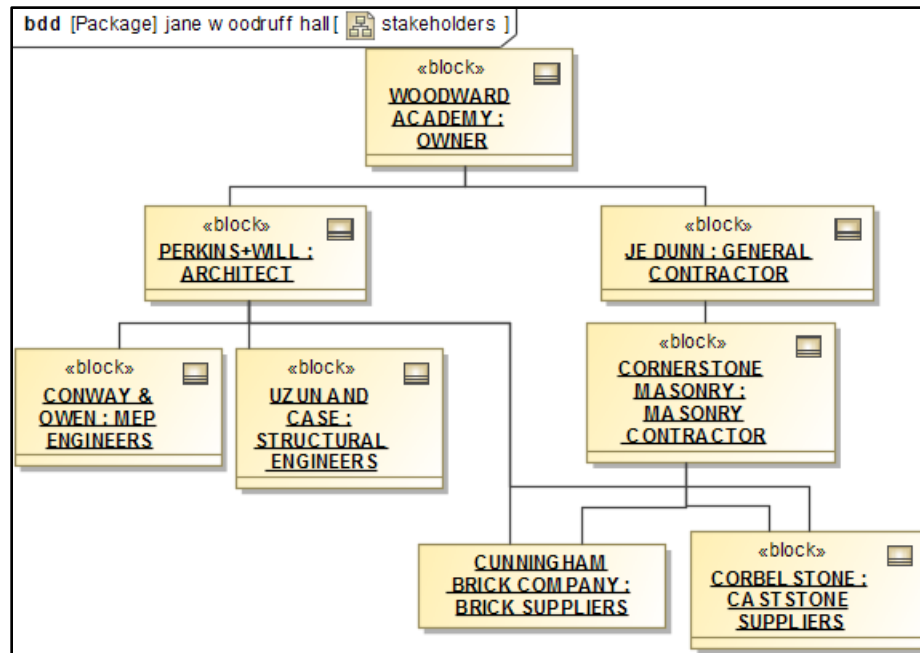


Figure 37 Woodruff Hall Project Stakeholders

5.3.3 Project Masonry Scope

The masonry scope on this project was dictated by the materials of the previous building that existed on site, the Founder's Hall, as well as the rest of campus. After reviewing documents, the architect identified “Woodward Blend” to be the brick color used on the Founder's Hall and other older buildings and decided to use it for the new project. The masonry supplier informed the architect that the current brick available under the same name did not match the ones previously used on the older buildings, because the clays used to manufacture the brick was now

different than what was used fifty years prior. This led to the owner's representative, the architect, and the masonry supplier holding collaborative meetings to select the proper masonry brick colors for the project. The other masonry materials used in the project were cast stone along the arches, parapet walls, and window coverings and CMU. According to the architect, the entire selection process involved the masonry supplier and the mason subcontractor (do Amaral et al., 2014).

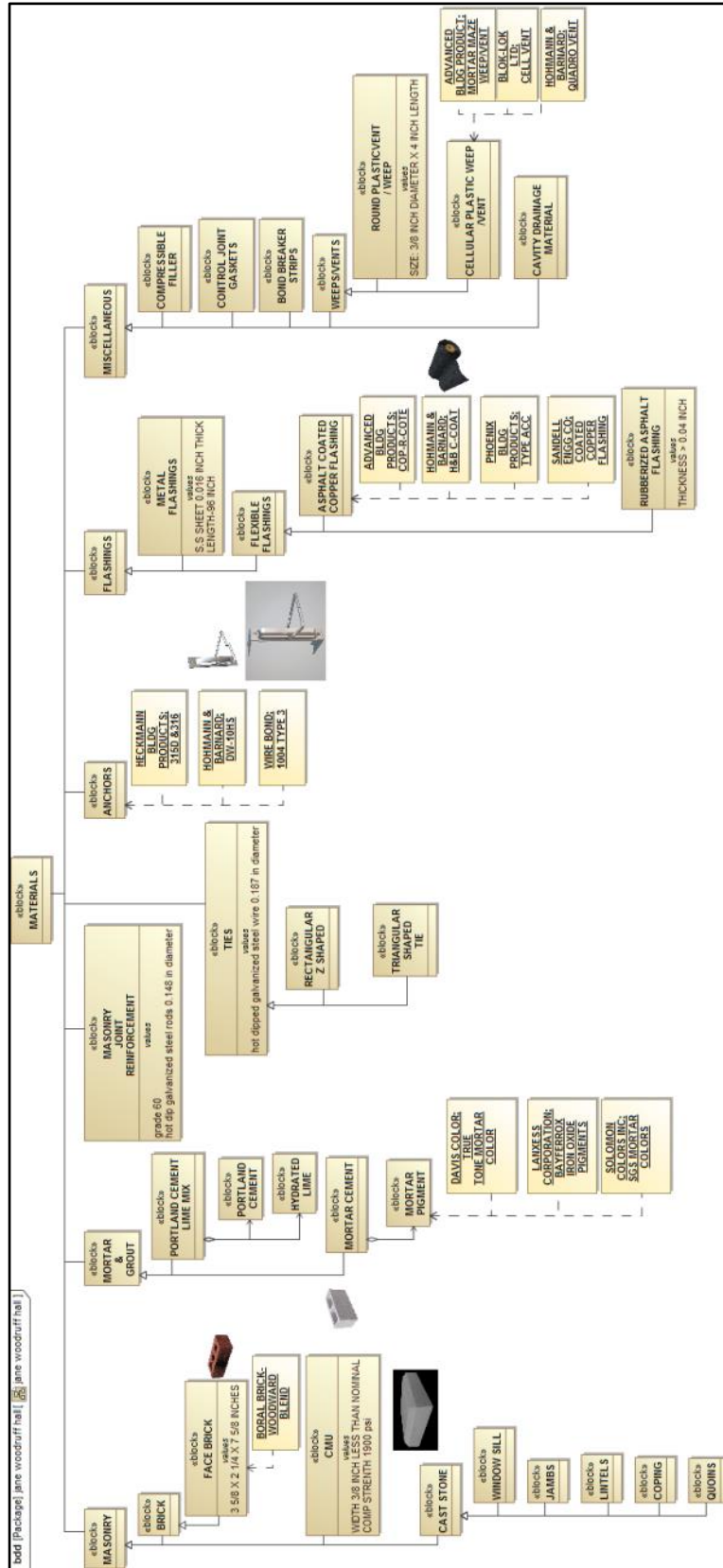


Figure 38 Woodruff Hall Project Masonry Scope

5.3.4 Project Phases

5.3.4.1 Contractor Coordination Phase

After receiving and reviewing the construction documents, the GC/CM organized the drawings and specifications and delegated them according to the specific jobs of the subcontractors. The GC/CM then established the internal schedule, developed the BIM model and assigned subcontractor tasks. The mason subcontractor coordinated with suppliers to determine masonry availability, extracted preliminary quantities, and prepared shop drawings. While creating the shop drawings, the mason subcontractor submitted RFI for the architect's review. This RFI had to be sent through the GC/CM to the architect. Figure shows the RFI Process.

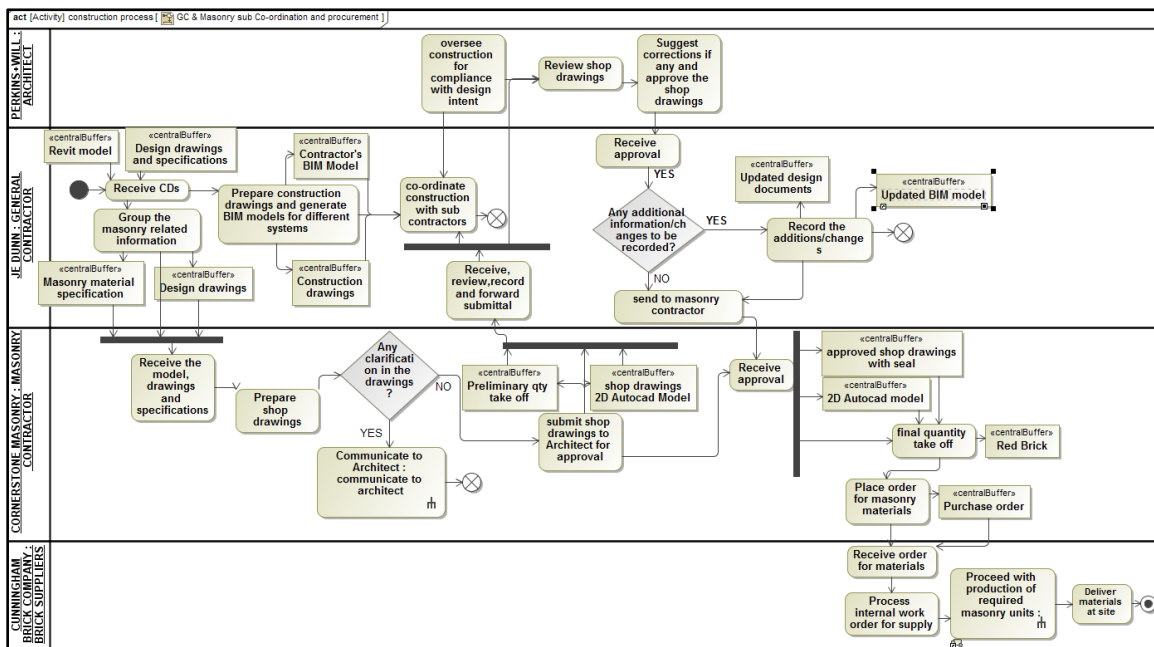


Figure 39 Woodruff Hall Contractor Coordination Phase

Similar to other RFI Processes, communication was done only through one channel and back (see Figure 40). The same path was followed for approving the shop drawings, only after which the mason subcontractor could place orders. The masonry order was placed with the supplier who was within 500 miles of the project site due to LEED certification and logistics. After internal processing, the masonry supplier delivered the units, which were stored in a dry location nearby before installation on site (see Figure 41).

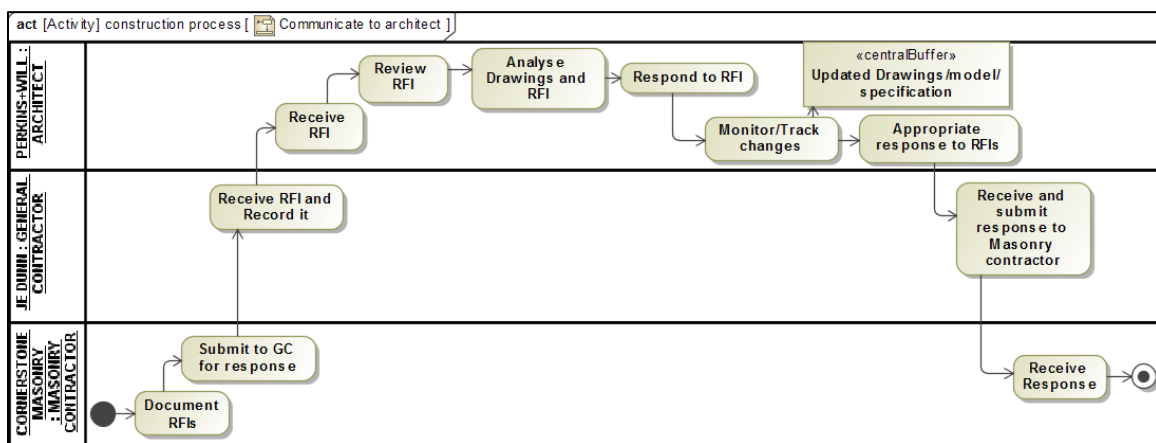


Figure 40 Communicate to the Architect

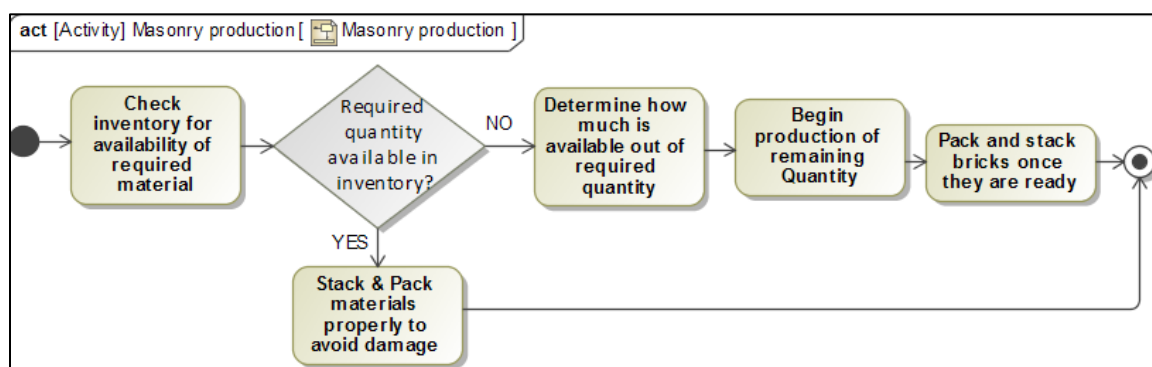


Figure 41 Masonry Production

5.3.4.2 Subcontractor Installation Phase

In this phase, the mason subcontractor installed the brick façade and also laid 4” CMU as support for the brick façade after the concrete subcontractor was finished setting the foundation. Here, we see a very linear process with no other stakeholders as the subcontractor focuses on the masonry scope (see Figures 42 to 45).

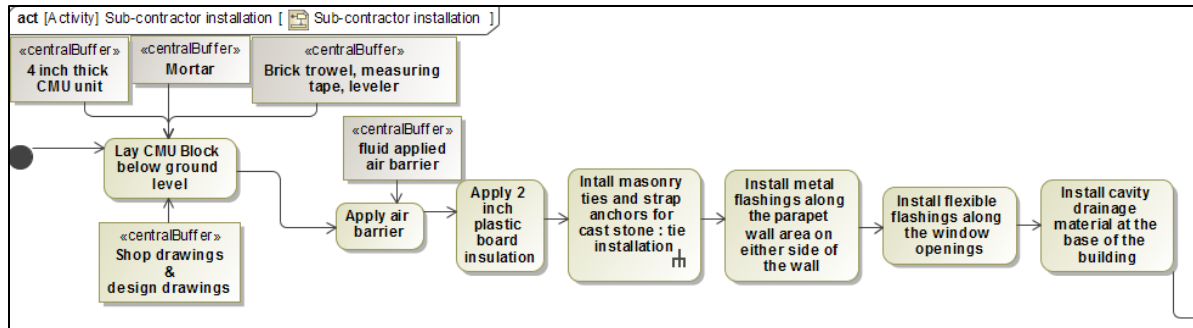


Figure 42 Woodruff Hall Subcontractor Installation, Part A

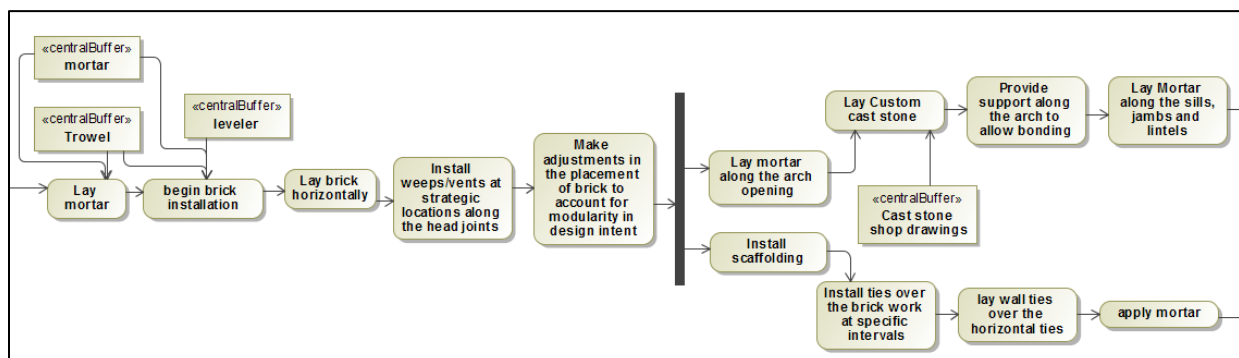


Figure 43 Woodruff Hall Subcontractor Installation, Part B

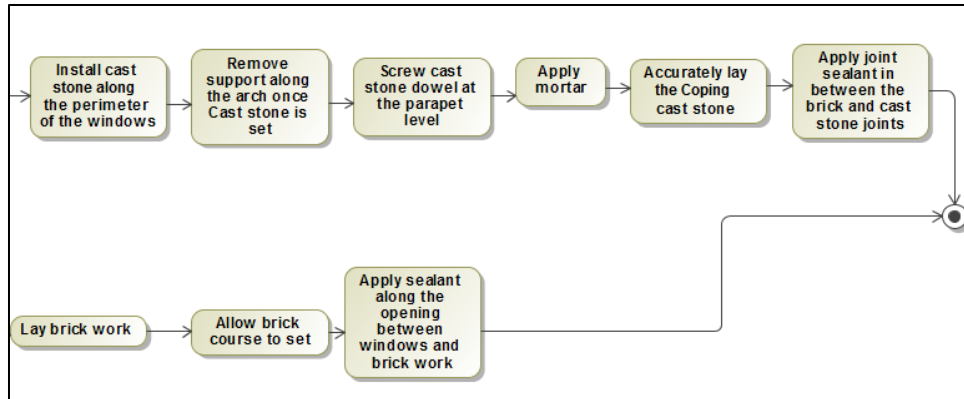


Figure 44 Woodruff Hall Subcontractor Installation, Part C

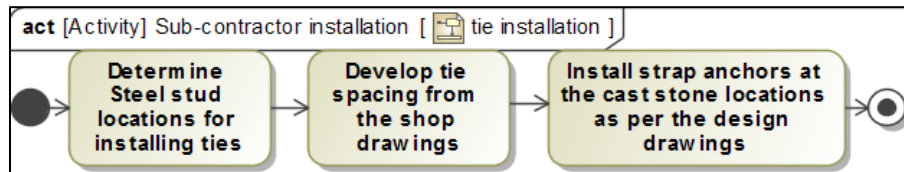


Figure 45 Install Masonry Ties and Strap Anchors for Cast Stone

During the installation of the brick façade, there was a conflict between the brick and light fixtures, due to the lack of prior coordination between the two trades and improper knowledge of site conditions and materials. As a result, the mason subcontractor had to rework the area around the light fixture to keep the appearance as uniform as possible (see Figure 46).



Figure 46 Conflict between Masonry and Light Fixtures

5.3.5 Conclusion and Lessons Learned

Once again, the construction process would very well benefit from an improved and more integrated communication and RFI process. Such a coordinated effort could essentially eliminate errors such as the physical clash with the light fixture on the brick façade. If the manufacturer were to provide a 3D/BIM model of the light fixture and masonry units were properly displayed, then the other project stakeholders could use this information early on and be able to properly detect the clash using BIM tools such as Revit.

CHAPTER 6

CONCLUSION AND NEXT STEPS

Current masonry construction processes are manual. Handling masonry units and laying brick and block are still done by hand and require great effort and labor by mason crews. Although advanced tools, such as robotic automation and pre-fabrication, are being researched and developed, they have not been fully realized or adopted in masonry construction practices (Hendry, 2001; Pritschow, Dalacker, Kurz, & Gaenssle, 1996). Construction documents are primarily created and maintained as paper copies, and any models created with software tools rarely contain useful masonry details. Site coordination involves face-to-face communication and relies heavily on paper drawings. Due to these weaknesses, the masonry construction industry may fall behind as the rest of the AEC industry continues to progress.

Throughout the case studies, these problems are evident and could be attributed to a few key issues: a disconnected industry and system, inadequate preparation, and the absence of sufficient management and organization. These issues could be addressed through early integration, early planning, and better onsite coordination.

For better integration, more information on masonry systems and components being used or considered is necessary, including geometric and functional coordination. A more cohesive design and analysis process between architects and engineers, including structural and MEP, would greatly improve the effort towards better and earlier project integration.

In order to have a well-planned project, we need to know what goes where, when, why, how, and by whom. Better planning leads to better scheduling and better quantity takeoffs. By knowing these details, considerations of labor and supply chain management could be made well

in advance. This will also improve the understanding of sequence dependencies among different assemblies throughout the project lifecycle. Overall, early planning will result in better cost estimation.

Better onsite coordination is crucial to having a construction project finish on time or early, with the least number of errors and high quality. Project stakeholders need access to the right information at the right time while on the construction site. Furthermore, crews, equipment, and supplies should be readily available and well-coordinated.

A systems modeling workflow can be used to help document and analyze the observations made in case studies. This model-based systems engineering tool can describe in detail the various processes and elements, including activities, stakeholders, tools, materials, and information, involved in masonry construction. SysML models allow us to view and access all the relevant data of specific masonry construction processes that cannot be achieved as easily through a paper-based workflow and current masonry industry processes.

The case studies and SysML documentation inform the necessities of BIM models and BIM-based processes in masonry construction. Today, BIM has minimal benefit for masonry construction, since BIM models only show 3D solids with nominal details of masonry buildings. This research begins to identify the who, what, when, where, why, and how of masonry constructions processes that are required for BIM implementation.

The initial findings from this research reinforce the fact that BIM for masonry will only be implemented successfully if we understand the various transactions, queries, and analyses that occur in the masonry industry and develop the software-enabled workflows that facilitate these activities. This benchmark project will be critical as the BIM-M research transitions to Phase III with BIM-M software specification (Building Information Modeling for Masonry, 2015). These

case studies are substantially important on their own. However, further case studies of similar and other masonry construction projects are needed. Ideally, each case study criterion for the masonry industry should be represented (i.e. one cell in the 3D visualization guide), so that the analyses and documentation are as comprehensive as possible. Furthermore, industry validation of these masonry construction processes and workflows are needed. This research provides the foundation for creating the requirements and tools to implement BIM for masonry.

REFERENCES

- Ashrafi, A., Ginn, B., Lee, J. S.-h., & McEwen, S. (2014). *Drew Charter Senior Academy. Presentation and Report*. Georgia Institute of Technology.
- Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3), 241-252. doi: doi:10.1061/(ASCE)LM.1943-5630.0000127
- Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research*, 64(11), 1199-1206. doi: <http://dx.doi.org/10.1016/j.jcsr.2008.07.011>
- Black, S. E., & Lynch, L. M. (2001). How to Compete: The Impact of Workplace Practices and Information Technology on Productivity. *Review of Economics and Statistics*, 83(3), 434-445. doi: 10.1162/00346530152480081
- Boschman, J. S., van der Molen, H. F., Sluiter, J. K., & Frings-Dresen, M. H. W. (2011). Occupational demands and health effects for bricklayers and construction supervisors: A systematic review. *American Journal of Industrial Medicine*, 54(1), 55-77. doi: 10.1002/ajim.20899
- Building Information Modeling for Masonry (Producer). (2014, July 30, 2014). Opportunities for BIM in Mason Contracting. [Webinar] Retrieved from <https://www.youtube.com/watch?v=Jwh1CYQGIIA>
- Building Information Modeling for Masonry. (2015). BIM-M Projects. from <http://www.bimformasonry.org/projects/>
- Byun, K. J. (2010). The US housing bubble and bust: impacts on employment. *Monthly Labor Review*, 3.
- CRC Construction Innovation. (2007). Adopting BIM for facilities management: Solutions for managing the Sydney Opera House. *Cooperative Research Center for Construction Innovation, Brisbane, Australia*.
- Curtis, B., Kellner, M. I., & Over, J. (1992). Process modeling. *Commun. ACM*, 35(9), 75-90. doi: 10.1145/130994.130998
- Davenport, T. H., & Short, J. (2003). Information technology and business process redesign. *Operations management: critical perspectives on business and management*, 1, 97.
- Demian, P., & Walters, D. (2013). The advantages of information management through building information modelling. *Construction Management and Economics*, 32(12), 1153-1165. doi: 10.1080/01446193.2013.777754

- Dermody, L., Ethayananth, E., Arul, N., & Li, Q. (2014). *Oxford College, Emory University: Fleming Hall*. Presentation and Report. Georgia Institute of Technology.
- do Amaral, G. G., Soundiah, S., Seenivasan, J., & Jia, Y. (2014). *Woodward Humanities Building: Jane Woodruff Hall*. Presentation and Report. Georgia Institute of Technology.
- Dong, M., & Chen, F. F. (2001). Process modeling and analysis of manufacturing supply chain networks using object-oriented Petri nets. *Robotics and Computer-Integrated Manufacturing*, 17(1–2), 121-129. doi: [http://dx.doi.org/10.1016/S0736-5845\(00\)00045-4](http://dx.doi.org/10.1016/S0736-5845(00)00045-4)
- Eastman, C., & Sacks, R. (2008). Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134(7), 517-526. doi: 10.1061/(ASCE)0733-9364(2008)134:7(517)
- Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Hoboken, New Jersey: John Wiley & Sons, Inc.
- Fernie, S., Leiringer, R., & Thorpe, T. (2006). Change in construction: a critical perspective. *Building Research and Information*, 34(2), 91-103. doi: 10.1080/09613210500491639
- Fisher, N., & Yin, S. L. (1992). *Information Management in a Contractor: A Model for the Flow of Project Data*. London, UK: Thomas Telford.
- Florez, L., Castro-Lacouture, D., & Gentry, R. (2014). *Workflows in Masonry Construction: Analysis of Labor Requirements*. Paper presented at the 9th International Masonry Conference 2014, Guimarães, Portugal.
- Friedenthal, S., Moore, A., & Steiner, R. (2012). *A Practical Guide to SysML: The Systems Modeling Language* (Second ed.). Waltham, MA: Morgan Kaufmann.
- Gentry, R., Eastman, C., Haymaker, J., & Lee, B. (2014). Development of Systems Models of Stakeholders and Exchanges Involved in Masonry Construction Projects. In D. Biggs (Ed.), *Building Information Modeling for Masonry Phase II Project, Project 2, Masonry BIM Benchmark: BIM-M*.
- Gilligan, B., & Kunz, J. (2007). VDC use in 2007: significant value, dramatic growth, and apparent business opportunity. *Center for Integrated Facility Engineering, Report TR171*.
- Green, P., & Rosemann, M. (2000). Integrated process modeling: An ontological evaluation. *Information Systems*, 25(2), 73-87. doi: [http://dx.doi.org/10.1016/S0306-4379\(00\)00010-7](http://dx.doi.org/10.1016/S0306-4379(00)00010-7)
- Green, S., Kao, C., & Larsen, G. (2009). Contextualist Research: Iterating between Methods While Following an Empirically Grounded Approach. *Journal of Construction Engineering and Management*, 136(1), 117-126. doi: 10.1061/(ASCE)CO.1943-7862.0000027

- Grimm, C. T. (1975). Mason Productivity. In A. W. Isberner (Ed.), *Masonry: Past and Present*, ASTM STP 589 (pp. 133-139). Philadelphia: American Society for Testing and Materials.
- Harty, C. (2005). Innovation in construction: a sociology of technology approach. *Building Research & Information*, 33(6), 512-522. doi: 10.1080/09613210500288605
- Hassanein, A., & Melin, J. (1997). Crew Design Methodology for Construction Contractors. *Journal of Construction Engineering and Management*, 123(3), 203-207. doi: 10.1061/(ASCE)0733-9364(1997)123:3(203)
- Havey, M. (2005). *Essential Business Process Modeling*: O'Reilly Media, Inc.
- Hendry, E. A. W. (2001). Masonry walls: materials and construction. *Construction and Building Materials*, 15(8), 323-330. doi: [http://dx.doi.org/10.1016/S0950-0618\(01\)00019-8](http://dx.doi.org/10.1016/S0950-0618(01)00019-8)
- Hunter, D. L. (1997). *Masonry Construction*. Prentice Hall: Upper Saddle River, NJ.
- Indulska, M., Green, P., Recker, J., & Rosemann, M. (2009). Business Process Modeling: Perceived Benefits. In A. F. Laender, S. Castano, U. Dayal, F. Casati & J. de Oliveira (Eds.), *Conceptual Modeling - ER 2009* (Vol. 5829, pp. 458-471): Springer Berlin Heidelberg.
- Kayali, O. (2008). Fly ash lightweight aggregates in high performance concrete. *Construction and Building Materials*, 22(12), 2393-2399. doi: <http://dx.doi.org/10.1016/j.conbuildmat.2007.09.001>
- Koo, B., & Fischer, M. (2000). Feasibility Study of 4D CAD in Commercial Construction. *Journal of Construction Engineering and Management*, 126(4), 251-260. doi: 10.1061/(ASCE)0733-9364(2000)126:4(251)
- Korkmaz, S., Messner, J. I., Riley, D. R., & Magent, C. (2010). High-Performance Green Building Design Process Modeling and Integrated Use of Visualization Tools. *Journal of Architectural Engineering*, 16(1), 37-45. doi: doi:10.1061/(ASCE)1076-0431(2010)16:1(37)
- Lake|Flato Architects, Inc. (2014). Georgia Tech Engineered Biosystems Building. Retrieved 9/27/14, from <http://www.lakeflato.com/projects/georgia-tech-engineered-biosystems/>
- Lee, S., Liu, Y., Chunduri, S., Solnosky, R. L., Messner, J. I., Leicht, R. M., & Anumba, C. J. (2012). Development of a Process Model to Support Integrated Design for Energy Efficient Buildings *Computing in Civil Engineering (2012)* (pp. 261-268).
- Masonry Contractors Association of America. (2015). History of Masonry. Retrieved April 4, 2015, from <http://www.masoncontractors.org/history/>
- McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management*, 11(3), 239-256. doi: [http://dx.doi.org/10.1016/0272-6963\(93\)90002-7](http://dx.doi.org/10.1016/0272-6963(93)90002-7)

- McGraw Hill Construction. (2014). The Business Value of BIM for Construction in Major Global Markets: How Contractors Around the World Are Driving Innovation With Building Information Modeling. In H. M. Bernstein (Ed.), *SmartMarket Report*. Bedford, MA.
- Melville, N., Kraemer, K., & Gurbaxani, V. (2004). Review: information technology and organizational performance: an integrative model of it business value. *MIS Q.*, 28(2), 283-322.
- Mitropoulos, P., & Memarian, B. (2013). Task Demands in Masonry Work: Sources, Performance Implications, and Management Strategies. *Journal of Construction Engineering and Management*, 139(5), 581-590. doi: doi:10.1061/(ASCE)CO.1943-7862.0000586
- National Institute of Building Sciences. (2007). United States National Building Information Modeling Standard, Version 1 - Part 1: Overview, Principles, and Methodologies. Washington, D.C.: National Institute of Building Sciences.
- Ng, S. T., & Tang, Z. (2010). Labour-intensive construction sub-contractors: Their critical success factors. *International Journal of Project Management*, 28(7), 732-740. doi: <http://dx.doi.org/10.1016/j.ijproman.2009.11.005>
- No Magic, Inc. (2015). SysML Plugin. from <http://www.nomagic.com/products/magicdraw-addons/sysml-plugin.html>
- Object Management Group, Inc. (2014). Introduction to OMG's Unified Modeling Language™ (UML®). Retrieved 9/27/14, from http://www.omg.org/gettingstarted/what_is_uml.htm
- Oregon Building Congress. (2015). Career Descriptions. Retrieved April 1, 2015, from <http://www.obcweb.com/careers-in-construction/career-descriptions.php>
- Phelps, A., & Horman, M. (2009). Ethnographic Theory-Building Research in Construction. *Journal of Construction Engineering and Management*, 136(1), 58-65. doi: 10.1061/(ASCE)CO.1943-7862.0000104
- Pink, S., Tutt, D., Dainty, A., & Gibb, A. (2010). Ethnographic methodologies for construction research: knowing, practice and interventions. *Building Research and Information*, 38(6), 647-659. doi: 10.1080/09613218.2010.512193
- Pritschow, G., Dalacker, M., Kurz, J., & Gaenssle, M. (1996). Technological aspects in the development of a mobile bricklaying robot. *Automation in Construction*, 5(1), 3-13. doi: [http://dx.doi.org/10.1016/0926-5805\(95\)00015-1](http://dx.doi.org/10.1016/0926-5805(95)00015-1)
- Ranallo, A., & Tarigopula, D. (2014). *Georgia Institute of Technology: Engineered Biosystems Building Cast Stone Workflows*. Presentation. Georgia Institute of Technology.

- Runeson, P., & Höst, M. (2009). Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14(2), 131-164. doi: 10.1007/s10664-008-9102-8
- Sacks, R., Eastman, C., & Lee, G. (2004). Process Model Perspectives on Management and Engineering Procedures in the Precast/Prestressed Concrete Industry. *Journal of Construction Engineering and Management*, 130(2), 206-215. doi: doi:10.1061/(ASCE)0733-9364(2004)130:2(206)
- Sanders, S. R., & Thomas, H. R. (1991). Factors affecting masonry-labor productivity. *Journal of Construction Engineering and Management*, 117(4), 626-644.
- Schneider, S., & Susi, P. (1994). Ergonomics and Construction: A Review of Potential Hazards in New Construction. *American Industrial Hygiene Association Journal*, 55(7), 635-649. doi: 10.1080/15428119491018727
- Shang, S., & Seddon, P. B. (2002). Assessing and managing the benefits of enterprise systems: the business manager's perspective. *Information Systems Journal*, 12(4), 271-299. doi: 10.1046/j.1365-2575.2002.00132.x
- Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., . . . Xue, H. (2010). Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced Engineering Informatics*, 24(2), 196-207. doi: http://dx.doi.org/10.1016/j.aei.2009.09.001
- Smith, R. C., Honkala, T. L., & Andres, C. K. (1979). *Masonry: Materials, Design, Construction*. Reston Publishing Company, Inc.: Reston, VA.
- Smith, R. P., & Morrow, J. A. (1999). Product development process modeling. *Design Studies*, 20(3), 237-261. doi: http://dx.doi.org/10.1016/S0142-694X(98)00018-0
- Stewart, R. A., Mohamed, S., & Daet, R. (2002). Strategic implementation of IT/IS projects in construction: a case study. *Automation in Construction*, 11(6), 681-694. doi: http://dx.doi.org/10.1016/S0926-5805(02)00009-2
- Stiehl, V. (2014). *Process-driven applications with BPMN*. Springer International Publishing: Switzerland.
- Teicholz, P., Goodrum, P., & Haas, C. (2001). U.S. Construction Labor Productivity Trends, 1970–1998. *Journal of Construction Engineering and Management*, 127(5), 427-429. doi: 10.1061/(ASCE)0733-9364(2001)127:5(427)
- Thomas, H. R., & Završki, I. (1999). Construction baseline productivity: Theory and practice. *Journal of Construction Engineering and Management*, 125(5), 295-303.
- Thomas, O., & Fellmann M.A, M. (2009). Semantic Process Modeling – Design and Implementation of an Ontology-based Representation of Business Processes. *Business & Information Systems Engineering*, 1(6), 438-451. doi: 10.1007/s12599-009-0078-8

- Tornberg, K., Jämsen, M., & Paranko, J. (2002). Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. *International Journal of Production Economics*, 79(1), 75-82. doi: [http://dx.doi.org/10.1016/S0925-5273\(00\)00179-1](http://dx.doi.org/10.1016/S0925-5273(00)00179-1)
- Wohed, P., van der Aalst, W. M. P., Dumas, M., ter Hofstede, A. H. M., & Russell, N. (2006). On the Suitability of BPMN for Business Process Modelling. In S. Dustdar, J. Fiadeiro & A. Sheth (Eds.), *Business Process Management* (Vol. 4102, pp. 161-176): Springer Berlin Heidelberg.
- Yang, J.-B., Wu, C.-T., & Tsai, C.-H. (2007). Selection of an ERP system for a construction firm in Taiwan: A case study. *Automation in Construction*, 16(6), 787-796. doi: <http://dx.doi.org/10.1016/j.autcon.2007.02.001>
- Young, N., Jones, S., Bernstein, H., & Gudge, J. (2008). SmartMarket report on building information modeling (BIM): Transforming design and construction to achieve greater industry productivity: McGraw-Hill Construction.
- Ashrafi, A., Ginn, B., Lee, J. S.-h., & McEwen, S. (2014). *Drew Charter Senior Academy*. Presentation and Report. Georgia Institute of Technology.
- Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3), 241-252. doi: [doi:10.1061/\(ASCE\)LM.1943-5630.0000127](https://doi.org/10.1061/(ASCE)LM.1943-5630.0000127)
- Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research*, 64(11), 1199-1206. doi: <http://dx.doi.org/10.1016/j.jcsr.2008.07.011>
- Black, S. E., & Lynch, L. M. (2001). How to Compete: The Impact of Workplace Practices and Information Technology on Productivity. *Review of Economics and Statistics*, 83(3), 434-445. doi: [10.1162/00346530152480081](https://doi.org/10.1162/00346530152480081)
- Boschman, J. S., van der Molen, H. F., Sluiter, J. K., & Frings-Dresen, M. H. W. (2011). Occupational demands and health effects for bricklayers and construction supervisors: A systematic review. *American Journal of Industrial Medicine*, 54(1), 55-77. doi: [10.1002/ajim.20899](https://doi.org/10.1002/ajim.20899)
- Building Information Modeling for Masonry (Producer). (2014, July 30, 2014). Opportunities for BIM in Mason Contracting. [Webinar] Retrieved from <https://www.youtube.com/watch?v=Jwh1CYQGIIA>
- Building Information Modeling for Masonry. (2015). BIM-M Projects. from <http://www.bimformasonry.org/projects/>
- Byun, K. J. (2010). The US housing bubble and bust: impacts on employment. *Monthly Labor Review*, 3.

- CRC Construction Innovation. (2007). Adopting BIM for facilities management: Solutions for managing the Sydney Opera House. *Cooperative Research Center for Construction Innovation, Brisbane, Australia*.
- Curtis, B., Kellner, M. I., & Over, J. (1992). Process modeling. *Commun. ACM*, 35(9), 75-90. doi: 10.1145/130994.130998
- Davenport, T. H., & Short, J. (2003). Information technology and business process redesign. *Operations management: critical perspectives on business and management*, 1, 97.
- Demian, P., & Walters, D. (2013). The advantages of information management through building information modelling. *Construction Management and Economics*, 32(12), 1153-1165. doi: 10.1080/01446193.2013.777754
- Dermody, L., Ethayananth, E., Arul, N., & Li, Q. (2014). *Oxford College, Emory University: Fleming Hall*. Presentation and Report. Georgia Institute of Technology.
- do Amaral, G. G., Soundiah, S., Seenivasan, J., & Jia, Y. (2014). *Woodward Humanities Building: Jane Woodruff Hall*. Presentation and Report. Georgia Institute of Technology.
- Dong, M., & Chen, F. F. (2001). Process modeling and analysis of manufacturing supply chain networks using object-oriented Petri nets. *Robotics and Computer-Integrated Manufacturing*, 17(1-2), 121-129. doi: [http://dx.doi.org/10.1016/S0736-5845\(00\)00045-4](http://dx.doi.org/10.1016/S0736-5845(00)00045-4)
- Eastman, C., & Sacks, R. (2008). Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134(7), 517-526. doi: 10.1061/(ASCE)0733-9364(2008)134:7(517)
- Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Hoboken, New Jersey: John Wiley & Sons, Inc.
- Fernie, S., Leiringer, R., & Thorpe, T. (2006). Change in construction: a critical perspective. *Building Research and Information*, 34(2), 91-103. doi: 10.1080/09613210500491639
- Fisher, N., & Yin, S. L. (1992). *Information Management in a Contractor: A Model for the Flow of Project Data*. London, UK: Thomas Telford.
- Florez, L., Castro-Lacouture, D., & Gentry, R. (2014). *Workflows in Masonry Construction: Analysis of Labor Requirements*. Paper presented at the 9th International Masonry Conference 2014, Guimarães, Portugal.
- Friedenthal, S., Moore, A., & Steiner, R. (2012). *A Practical Guide to SysML: The Systems Modeling Language* (Second ed.). Waltham, MA: Morgan Kaufmann.
- Gentry, R., Eastman, C., Haymaker, J., & Lee, B. (2014). Development of Systems Models of Stakeholders and Exchanges Involved in Masonry Construction Projects. In D. Biggs

- (Ed.), *Building Information Modeling for Masonry Phase II Project, Project 2, Masonry BIM Benchmark: BIM-M*.
- Gilligan, B., & Kunz, J. (2007). VDC use in 2007: significant value, dramatic growth, and apparent business opportunity. *Center for Integrated Facility Engineering, Report TR171*.
- Green, P., & Rosemann, M. (2000). Integrated process modeling: An ontological evaluation. *Information Systems*, 25(2), 73-87. doi: [http://dx.doi.org/10.1016/S0306-4379\(00\)00010-7](http://dx.doi.org/10.1016/S0306-4379(00)00010-7)
- Green, S., Kao, C., & Larsen, G. (2009). Contextualist Research: Iterating between Methods While Following an Empirically Grounded Approach. *Journal of Construction Engineering and Management*, 136(1), 117-126. doi: 10.1061/(ASCE)CO.1943-7862.0000027
- Grimm, C. T. (1975). Mason Productivity. In A. W. Isberner (Ed.), *Masonry: Past and Present*, ASTM STP 589 (pp. 133-139). Philadelphia: American Society for Testing and Materials.
- Harty, C. (2005). Innovation in construction: a sociology of technology approach. *Building Research & Information*, 33(6), 512-522. doi: 10.1080/09613210500288605
- Hassanein, A., & Melin, J. (1997). Crew Design Methodology for Construction Contractors. *Journal of Construction Engineering and Management*, 123(3), 203-207. doi: 10.1061/(ASCE)0733-9364(1997)123:3(203)
- Havey, M. (2005). *Essential Business Process Modeling*: O'Reilly Media, Inc.
- Hunter, D. L. (1997). *Masonry Construction*. Prentice Hall: Upper Saddle River, NJ.
- Indulska, M., Green, P., Recker, J., & Rosemann, M. (2009). Business Process Modeling: Perceived Benefits. In A. F. Laender, S. Castano, U. Dayal, F. Casati & J. de Oliveira (Eds.), *Conceptual Modeling - ER 2009* (Vol. 5829, pp. 458-471): Springer Berlin Heidelberg.
- Kayali, O. (2008). Fly ash lightweight aggregates in high performance concrete. *Construction and Building Materials*, 22(12), 2393-2399. doi: <http://dx.doi.org/10.1016/j.conbuildmat.2007.09.001>
- Koo, B., & Fischer, M. (2000). Feasibility Study of 4D CAD in Commercial Construction. *Journal of Construction Engineering and Management*, 126(4), 251-260. doi: 10.1061/(ASCE)0733-9364(2000)126:4(251)
- Korkmaz, S., Messner, J. I., Riley, D. R., & Magent, C. (2010). High-Performance Green Building Design Process Modeling and Integrated Use of Visualization Tools. *Journal of Architectural Engineering*, 16(1), 37-45. doi: doi:10.1061/(ASCE)1076-0431(2010)16:1(37)

- Lake|Flato Architects, Inc. (2014). Georgia Tech Engineered Biosystems Building. Retrieved 9/27/14, from <http://www.lakeflato.com/projects/georgia-tech-engineered-biosystems/>
- Lee, S., Liu, Y., Chunduri, S., Solnosky, R. L., Messner, J. I., Leicht, R. M., & Anumba, C. J. (2012). Development of a Process Model to Support Integrated Design for Energy Efficient Buildings *Computing in Civil Engineering (2012)* (pp. 261-268).
- Masonry Contractors Association of America. (2015). History of Masonry. Retrieved April 4, 2015, from <http://www.masoncontractors.org/history/>
- McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management*, 11(3), 239-256. doi: [http://dx.doi.org/10.1016/0272-6963\(93\)90002-7](http://dx.doi.org/10.1016/0272-6963(93)90002-7)
- McGraw Hill Construction. (2014). The Business Value of BIM for Construction in Major Global Markets: How Contractors Around the World Are Driving Innovation With Building Information Modeling. In H. M. Bernstein (Ed.), *SmartMarket Report*. Bedford, MA.
- Melville, N., Kraemer, K., & Gurbaxani, V. (2004). Review: information technology and organizational performance: an integrative model of it business value. *MIS Q.*, 28(2), 283-322.
- Mitropoulos, P., & Memarian, B. (2013). Task Demands in Masonry Work: Sources, Performance Implications, and Management Strategies. *Journal of Construction Engineering and Management*, 139(5), 581-590. doi: doi:10.1061/(ASCE)CO.1943-7862.0000586
- National Institute of Building Sciences. (2007). United States National Building Information Modeling Standard, Version 1 - Part 1: Overview, Principles, and Methodologies. Washington, D.C.: National Institute of Building Sciences.
- Ng, S. T., & Tang, Z. (2010). Labour-intensive construction sub-contractors: Their critical success factors. *International Journal of Project Management*, 28(7), 732-740. doi: <http://dx.doi.org/10.1016/j.ijproman.2009.11.005>
- No Magic, Inc. (2015). SysML Plugin. from <http://www.nomagic.com/products/magicdraw-addons/sysml-plugin.html>
- Object Management Group, Inc. (2014). Introduction to OMG's Unified Modeling Language™ (UML®). Retrieved 9/27/14, from http://www.omg.org/gettingstarted/what_is_uml.htm
- Oregon Building Congress. (2015). Career Descriptions. Retrieved April 1, 2015, from <http://www.obcweb.com/careers-in-construction/career-descriptions.php>
- Phelps, A., & Horman, M. (2009). Ethnographic Theory-Building Research in Construction. *Journal of Construction Engineering and Management*, 136(1), 58-65. doi: 10.1061/(ASCE)CO.1943-7862.0000104

- Pink, S., Tutt, D., Dainty, A., & Gibb, A. (2010). Ethnographic methodologies for construction research: knowing, practice and interventions. *Building Research and Information*, 38(6), 647-659. doi: 10.1080/09613218.2010.512193
- Pritschow, G., Dalacker, M., Kurz, J., & Gaenssle, M. (1996). Technological aspects in the development of a mobile bricklaying robot. *Automation in Construction*, 5(1), 3-13. doi: [http://dx.doi.org/10.1016/0926-5805\(95\)00015-1](http://dx.doi.org/10.1016/0926-5805(95)00015-1)
- Ranallo, A., & Tarigopula, D. (2014). *Georgia Institute of Technology: Engineered Biosystems Building Cast Stone Workflows*. Presentation. Georgia Institute of Technology.
- Runeson, P., & Höst, M. (2009). Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14(2), 131-164. doi: 10.1007/s10664-008-9102-8
- Sacks, R., Eastman, C., & Lee, G. (2004). Process Model Perspectives on Management and Engineering Procedures in the Precast/Prestressed Concrete Industry. *Journal of Construction Engineering and Management*, 130(2), 206-215. doi: doi:10.1061/(ASCE)0733-9364(2004)130:2(206)
- Sanders, S. R., & Thomas, H. R. (1991). Factors affecting masonry-labor productivity. *Journal of Construction Engineering and Management*, 117(4), 626-644.
- Schneider, S., & Susi, P. (1994). Ergonomics and Construction: A Review of Potential Hazards in New Construction. *American Industrial Hygiene Association Journal*, 55(7), 635-649. doi: 10.1080/15428119491018727
- Shang, S., & Seddon, P. B. (2002). Assessing and managing the benefits of enterprise systems: the business manager's perspective. *Information Systems Journal*, 12(4), 271-299. doi: 10.1046/j.1365-2575.2002.00132.x
- Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., . . . Xue, H. (2010). Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced Engineering Informatics*, 24(2), 196-207. doi: <http://dx.doi.org/10.1016/j.aei.2009.09.001>
- Smith, R. C., Honkala, T. L., & Andres, C. K. (1979). *Masonry: Materials, Design, Construction*. Reston Publishing Company, Inc.: Reston, VA.
- Smith, R. P., & Morrow, J. A. (1999). Product development process modeling. *Design Studies*, 20(3), 237-261. doi: [http://dx.doi.org/10.1016/S0142-694X\(98\)00018-0](http://dx.doi.org/10.1016/S0142-694X(98)00018-0)
- Stewart, R. A., Mohamed, S., & Daet, R. (2002). Strategic implementation of IT/IS projects in construction: a case study. *Automation in Construction*, 11(6), 681-694. doi: [http://dx.doi.org/10.1016/S0926-5805\(02\)00009-2](http://dx.doi.org/10.1016/S0926-5805(02)00009-2)
- Stiehl, V. (2014). *Process-driven applications with BPMN*. Springer International Publishing: Switzerland.

- Teicholz, P., Goodrum, P., & Haas, C. (2001). U.S. Construction Labor Productivity Trends, 1970–1998. *Journal of Construction Engineering and Management*, 127(5), 427-429. doi: 10.1061/(ASCE)0733-9364(2001)127:5(427)
- Thomas, H. R., & Završki, I. (1999). Construction baseline productivity: Theory and practice. *Journal of Construction Engineering and Management*, 125(5), 295-303.
- Thomas, O., & Fellmann M.A, M. (2009). Semantic Process Modeling – Design and Implementation of an Ontology-based Representation of Business Processes. *Business & Information Systems Engineering*, 1(6), 438-451. doi: 10.1007/s12599-009-0078-8
- Tornberg, K., Jämsen, M., & Paranko, J. (2002). Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. *International Journal of Production Economics*, 79(1), 75-82. doi: [http://dx.doi.org/10.1016/S0925-5273\(00\)00179-1](http://dx.doi.org/10.1016/S0925-5273(00)00179-1)
- Wohed, P., van der Aalst, W. M. P., Dumas, M., ter Hofstede, A. H. M., & Russell, N. (2006). On the Suitability of BPMN for Business Process Modelling. In S. Dustdar, J. Fiadeiro & A. Sheth (Eds.), *Business Process Management* (Vol. 4102, pp. 161-176): Springer Berlin Heidelberg.
- Yang, J.-B., Wu, C.-T., & Tsai, C.-H. (2007). Selection of an ERP system for a construction firm in Taiwan: A case study. *Automation in Construction*, 16(6), 787-796. doi: <http://dx.doi.org/10.1016/j.autcon.2007.02.001>
- Young, N., Jones, S., Bernstein, H., & Gudgel, J. (2008). SmartMarket report on building information modeling (BIM): Transforming design and construction to achieve greater industry productivity: McGraw-Hill Construction.
- Ashrafi, A., Ginn, B., Lee, J. S.-h., & McEwen, S. (2014). *Drew Charter Senior Academy*. Presentation and Report. Georgia Institute of Technology.
- Azhar, S. (2011). Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry. *Leadership and Management in Engineering*, 11(3), 241-252. doi: doi:10.1061/(ASCE)LM.1943-5630.0000127
- Baddoo, N. R. (2008). Stainless steel in construction: A review of research, applications, challenges and opportunities. *Journal of Constructional Steel Research*, 64(11), 1199-1206. doi: <http://dx.doi.org/10.1016/j.jcsr.2008.07.011>
- Black, S. E., & Lynch, L. M. (2001). How to Compete: The Impact of Workplace Practices and Information Technology on Productivity. *Review of Economics and Statistics*, 83(3), 434-445. doi: 10.1162/00346530152480081
- Boschman, J. S., van der Molen, H. F., Sluiter, J. K., & Frings-Dresen, M. H. W. (2011). Occupational demands and health effects for bricklayers and construction supervisors: A systematic review. *American Journal of Industrial Medicine*, 54(1), 55-77. doi: 10.1002/ajim.20899

- Building Information Modeling for Masonry (Producer). (2014, July 30, 2014). Opportunities for BIM in Mason Contracting. [Webinar] Retrieved from <https://www.youtube.com/watch?v=Jwh1CYQGIIA>
- Building Information Modeling for Masonry. (2015). BIM-M Projects. from <http://www.bimformasonry.org/projects/>
- Byun, K. J. (2010). The US housing bubble and bust: impacts on employment. *Monthly Labor Review*, 3.
- CRC Construction Innovation. (2007). Adopting BIM for facilities management: Solutions for managing the Sydney Opera House. *Cooperative Research Center for Construction Innovation, Brisbane, Australia*.
- Curtis, B., Kellner, M. I., & Over, J. (1992). Process modeling. *Commun. ACM*, 35(9), 75-90. doi: 10.1145/130994.130998
- Davenport, T. H., & Short, J. (2003). Information technology and business process redesign. *Operations management: critical perspectives on business and management*, 1, 97.
- Demian, P., & Walters, D. (2013). The advantages of information management through building information modelling. *Construction Management and Economics*, 32(12), 1153-1165. doi: 10.1080/01446193.2013.777754
- Dermody, L., Ethayananth, E., Arul, N., & Li, Q. (2014). *Oxford College, Emory University: Fleming Hall*. Presentation and Report. Georgia Institute of Technology.
- do Amaral, G. G., Soundiah, S., Seenivasan, J., & Jia, Y. (2014). *Woodward Humanities Building: Jane Woodruff Hall*. Presentation and Report. Georgia Institute of Technology.
- Dong, M., & Chen, F. F. (2001). Process modeling and analysis of manufacturing supply chain networks using object-oriented Petri nets. *Robotics and Computer-Integrated Manufacturing*, 17(1-2), 121-129. doi: [http://dx.doi.org/10.1016/S0736-5845\(00\)00045-4](http://dx.doi.org/10.1016/S0736-5845(00)00045-4)
- Eastman, C., & Sacks, R. (2008). Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*, 134(7), 517-526. doi: 10.1061/(ASCE)0733-9364(2008)134:7(517)
- Eastman, C., Teicholz, P., Sacks, R., & Liston, K. (2011). *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*. Hoboken, New Jersey: John Wiley & Sons, Inc.
- Fernie, S., Leiringer, R., & Thorpe, T. (2006). Change in construction: a critical perspective. *Building Research and Information*, 34(2), 91-103. doi: 10.1080/09613210500491639
- Fisher, N., & Yin, S. L. (1992). *Information Management in a Contractor: A Model for the Flow of Project Data*. London, UK: Thomas Telford.

- Florez, L., Castro-Lacouture, D., & Gentry, R. (2014). *Workflows in Masonry Construction: Analysis of Labor Requirements*. Paper presented at the 9th International Masonry Conference 2014, Guimarães, Portugal.
- Friedenthal, S., Moore, A., & Steiner, R. (2012). *A Practical Guide to SysML: The Systems Modeling Language* (Second ed.). Waltham, MA: Morgan Kaufmann.
- Gentry, R., Eastman, C., Haymaker, J., & Lee, B. (2014). Development of Systems Models of Stakeholders and Exchanges Involved in Masonry Construction Projects. In D. Biggs (Ed.), *Building Information Modeling for Masonry Phase II Project, Project 2, Masonry BIM Benchmark: BIM-M*.
- Gilligan, B., & Kunz, J. (2007). VDC use in 2007: significant value, dramatic growth, and apparent business opportunity. *Center for Integrated Facility Engineering, Report TR171*.
- Green, P., & Rosemann, M. (2000). Integrated process modeling: An ontological evaluation. *Information Systems*, 25(2), 73-87. doi: [http://dx.doi.org/10.1016/S0306-4379\(00\)00010-7](http://dx.doi.org/10.1016/S0306-4379(00)00010-7)
- Green, S., Kao, C., & Larsen, G. (2009). Contextualist Research: Iterating between Methods While Following an Empirically Grounded Approach. *Journal of Construction Engineering and Management*, 136(1), 117-126. doi: 10.1061/(ASCE)CO.1943-7862.0000027
- Grimm, C. T. (1975). Mason Productivity. In A. W. Isberner (Ed.), *Masonry: Past and Present, ASTM STP 589* (pp. 133-139). Philadelphia: American Society for Testing and Materials.
- Harty, C. (2005). Innovation in construction: a sociology of technology approach. *Building Research & Information*, 33(6), 512-522. doi: 10.1080/09613210500288605
- Hassanein, A., & Melin, J. (1997). Crew Design Methodology for Construction Contractors. *Journal of Construction Engineering and Management*, 123(3), 203-207. doi: 10.1061/(ASCE)0733-9364(1997)123:3(203)
- Havey, M. (2005). *Essential Business Process Modeling*: O'Reilly Media, Inc.
- Hunter, D. L. (1997). *Masonry Construction*. Prentice Hall: Upper Saddle River, NJ.
- Indulska, M., Green, P., Recker, J., & Rosemann, M. (2009). Business Process Modeling: Perceived Benefits. In A. F. Laender, S. Castano, U. Dayal, F. Casati & J. de Oliveira (Eds.), *Conceptual Modeling - ER 2009* (Vol. 5829, pp. 458-471): Springer Berlin Heidelberg.
- Kayali, O. (2008). Fly ash lightweight aggregates in high performance concrete. *Construction and Building Materials*, 22(12), 2393-2399. doi: <http://dx.doi.org/10.1016/j.conbuildmat.2007.09.001>

- Koo, B., & Fischer, M. (2000). Feasibility Study of 4D CAD in Commercial Construction. *Journal of Construction Engineering and Management*, 126(4), 251-260. doi: 10.1061/(ASCE)0733-9364(2000)126:4(251)
- Korkmaz, S., Messner, J. I., Riley, D. R., & Magent, C. (2010). High-Performance Green Building Design Process Modeling and Integrated Use of Visualization Tools. *Journal of Architectural Engineering*, 16(1), 37-45. doi: doi:10.1061/(ASCE)1076-0431(2010)16:1(37)
- Lake|Flato Architects, Inc. (2014). Georgia Tech Engineered Biosystems Building. Retrieved 9/27/14, from <http://www.lakeflato.com/projects/georgia-tech-engineered-biosystems/>
- Lee, S., Liu, Y., Chunduri, S., Solnosky, R. L., Messner, J. I., Leicht, R. M., & Anumba, C. J. (2012). Development of a Process Model to Support Integrated Design for Energy Efficient Buildings *Computing in Civil Engineering (2012)* (pp. 261-268).
- Masonry Contractors Association of America. (2015). History of Masonry. Retrieved April 4, 2015, from <http://www.masoncontractors.org/history/>
- McCutcheon, D. M., & Meredith, J. R. (1993). Conducting case study research in operations management. *Journal of Operations Management*, 11(3), 239-256. doi: [http://dx.doi.org/10.1016/0272-6963\(93\)90002-7](http://dx.doi.org/10.1016/0272-6963(93)90002-7)
- McGraw Hill Construction. (2014). The Business Value of BIM for Construction in Major Global Markets: How Contractors Around the World Are Driving Innovation With Building Information Modeling. In H. M. Bernstein (Ed.), *SmartMarket Report*. Bedford, MA.
- Melville, N., Kraemer, K., & Gurbaxani, V. (2004). Review: information technology and organizational performance: an integrative model of it business value. *MIS Q.*, 28(2), 283-322.
- Mitropoulos, P., & Memarian, B. (2013). Task Demands in Masonry Work: Sources, Performance Implications, and Management Strategies. *Journal of Construction Engineering and Management*, 139(5), 581-590. doi: doi:10.1061/(ASCE)CO.1943-7862.0000586
- National Institute of Building Sciences. (2007). United States National Building Information Modeling Standard, Version 1 - Part 1: Overview, Principles, and Methodologies. Washington, D.C.: National Institute of Building Sciences.
- Ng, S. T., & Tang, Z. (2010). Labour-intensive construction sub-contractors: Their critical success factors. *International Journal of Project Management*, 28(7), 732-740. doi: <http://dx.doi.org/10.1016/j.ijproman.2009.11.005>
- No Magic, Inc. (2015). SysML Plugin. from <http://www.nomagic.com/products/magicdraw-addons/sysml-plugin.html>

- Object Management Group, Inc. (2014). Introduction to OMG's Unified Modeling Language™ (UML®). Retrieved 9/27/14, from http://www.omg.org/gettingstarted/what_is_uml.htm
- Oregon Building Congress. (2015). Career Descriptions. Retrieved April 1, 2015, from <http://www.obcweb.com/careers-in-construction/career-descriptions.php>
- Phelps, A., & Horman, M. (2009). Ethnographic Theory-Building Research in Construction. *Journal of Construction Engineering and Management*, 136(1), 58-65. doi: 10.1061/(ASCE)CO.1943-7862.0000104
- Pink, S., Tutt, D., Dainty, A., & Gibb, A. (2010). Ethnographic methodologies for construction research: knowing, practice and interventions. *Building Research and Information*, 38(6), 647-659. doi: 10.1080/09613218.2010.512193
- Ranallo, A., & Tarigopula, D. (2014). *Georgia Institute of Technology: Engineered Biosystems Building Cast Stone Workflows*. Presentation. Georgia Institute of Technology.
- Runeson, P., & Höst, M. (2009). Guidelines for conducting and reporting case study research in software engineering. *Empirical Software Engineering*, 14(2), 131-164. doi: 10.1007/s10664-008-9102-8
- Sacks, R., Eastman, C., & Lee, G. (2004). Process Model Perspectives on Management and Engineering Procedures in the Precast/Prestressed Concrete Industry. *Journal of Construction Engineering and Management*, 130(2), 206-215. doi: doi:10.1061/(ASCE)0733-9364(2004)130:2(206)
- Sanders, S. R., & Thomas, H. R. (1991). Factors affecting masonry-labor productivity. *Journal of Construction Engineering and Management*, 117(4), 626-644.
- Schneider, S., & Susi, P. (1994). Ergonomics and Construction: A Review of Potential Hazards in New Construction. *American Industrial Hygiene Association Journal*, 55(7), 635-649. doi: 10.1080/15428119491018727
- Shang, S., & Seddon, P. B. (2002). Assessing and managing the benefits of enterprise systems: the business manager's perspective. *Information Systems Journal*, 12(4), 271-299. doi: 10.1046/j.1365-2575.2002.00132.x
- Shen, W., Hao, Q., Mak, H., Neelamkavil, J., Xie, H., Dickinson, J., . . . Xue, H. (2010). Systems integration and collaboration in architecture, engineering, construction, and facilities management: A review. *Advanced Engineering Informatics*, 24(2), 196-207. doi: <http://dx.doi.org/10.1016/j.aei.2009.09.001>
- Smith, R. C., Honkala, T. L., & Andres, C. K. (1979). *Masonry: Materials, Design, Construction*. Reston Publishing Company, Inc.: Reston, VA.
- Smith, R. P., & Morrow, J. A. (1999). Product development process modeling. *Design Studies*, 20(3), 237-261. doi: [http://dx.doi.org/10.1016/S0142-694X\(98\)00018-0](http://dx.doi.org/10.1016/S0142-694X(98)00018-0)

- Stewart, R. A., Mohamed, S., & Daet, R. (2002). Strategic implementation of IT/IS projects in construction: a case study. *Automation in Construction*, 11(6), 681-694. doi: [http://dx.doi.org/10.1016/S0926-5805\(02\)00009-2](http://dx.doi.org/10.1016/S0926-5805(02)00009-2)
- Stiehl, V. (2014). *Process-driven applications with BPMN*. Springer International Publishing: Switzerland.
- Teicholz, P., Goodrum, P., & Haas, C. (2001). U.S. Construction Labor Productivity Trends, 1970–1998. *Journal of Construction Engineering and Management*, 127(5), 427-429. doi: 10.1061/(ASCE)0733-9364(2001)127:5(427)
- Thomas, H. R., & Završki, I. (1999). Construction baseline productivity: Theory and practice. *Journal of Construction Engineering and Management*, 125(5), 295-303.
- Thomas, O., & Fellmann M.A, M. (2009). Semantic Process Modeling – Design and Implementation of an Ontology-based Representation of Business Processes. *Business & Information Systems Engineering*, 1(6), 438-451. doi: 10.1007/s12599-009-0078-8
- Tornberg, K., Jämsen, M., & Paranko, J. (2002). Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. *International Journal of Production Economics*, 79(1), 75-82. doi: [http://dx.doi.org/10.1016/S0925-5273\(00\)00179-1](http://dx.doi.org/10.1016/S0925-5273(00)00179-1)
- Wohed, P., van der Aalst, W. M. P., Dumas, M., ter Hofstede, A. H. M., & Russell, N. (2006). On the Suitability of BPMN for Business Process Modelling. In S. Dustdar, J. Fiadeiro & A. Sheth (Eds.), *Business Process Management* (Vol. 4102, pp. 161-176): Springer Berlin Heidelberg.
- Yang, J.-B., Wu, C.-T., & Tsai, C.-H. (2007). Selection of an ERP system for a construction firm in Taiwan: A case study. *Automation in Construction*, 16(6), 787-796. doi: <http://dx.doi.org/10.1016/j.autcon.2007.02.001>
- Young, N., Jones, S., Bernstein, H., & Gudgel, J. (2008). SmartMarket report on building information modeling (BIM): Transforming design and construction to achieve greater industry productivity: McGraw-Hill Construction.